CF$_3$I Gas and Its Mixtures: Potential for Electrical Insulation

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SUMMARY

SF$_6$ is a potent greenhouse gas with a global warming potential (GWP) of 23,900 times that of CO$_2$ and atmospheric lifetime exceeding 1000 years. For this reason, there has been research into alternative insulation gases with the aim of reduced SF$_6$ gas content in high-voltage equipment. The research, so far, into alternative gases has shown that CF$_3$I and its gas mixtures have promising dielectric properties comparable to those of SF$_6$. This paper provides an overview of research into alternative gases to SF$_6$. These include laboratory tests on the gases and initial applications to electrical power equipment.

In this work, the dielectric strength of CF$_3$I and its mixtures with CO$_2$ was experimentally examined under lightning impulse conditions. To investigate the properties of CF$_3$I, a steel cylindrical pressure vessel has been built with a pair of brass electrodes inside. Uniform and non-uniform field behaviour was generated by using different electrode arrangements. Tests were carried out on gas mixtures of CF$_3$I-CO$_2$ (in particular 30:70%) at 0.1 MPa (abs). It was found that, for various gap geometries (rod-plane and plane-plane electrodes) and lengths, CF$_3$I mixtures exhibit promising breakdown characteristics comparable to those of SF$_6$ gas based on the measured 50% breakdown voltage (U$_{50}$). These encouraging results led to a trial of CF$_3$I as the insulation gas on practical 11 kV low-current switches and circuit breakers. In particular, a Ring Main Unit (RMU) was tested to compare the performance of 30:70% CF$_3$I-CO$_2$ mixture with 100% SF$_6$ when subjected to the rated lightning impulse withstand voltage (U$_p$). This work demonstrated the feasibility of replacing SF$_6$ with the new gas mixture without the need to modify the geometry of the switchgear. However, research has shown that interruption of arc currents is rather limited to up to about 100 A [1]; beyond this level further research is required.

The fundamental laboratory experiments on the new gas were extended to coaxial geometries replicating electric field magnitudes (160-200 kV/cm) as found in a 400 kV GIS/GIL under lightning voltage impulse of 1425 kV. The ultimate aim of this work on coaxial models is the feasibility of GIL using CF$_3$I mixtures which is investigated in a parallel project. An EMTP-ATP model has been developed to study the characteristics of GIL as a long transmission system. Steady state results obtained suggest that reactive power compensation is not required for up to 300 km. Simulation results show that GIL using CF$_3$I gas mixtures may provide an attractive alternative to long cable and overhead lines.

KEYWORDS

Gas Insulated Lines (GIL), Gas Insulated Switchgear (GIS), Trifluoriodomethane (CF$_3$I), Sulfur Hexafluoride (SF$_6$).

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1. Introduction

$\text{SF}_6$ is an electronegative gas and it has dielectric strength three times higher than air. The outstanding properties of $\text{SF}_6$ have resulted in its extensive use as an insulation gas in high-voltage equipment. On the other hand, it is a highly potent greenhouse gas due to its high global warming potential, around 23,900 times that of $\text{CO}_2$. Alternatives insulation gases to replace $\text{SF}_6$ have been investigated in recent decades and one emerging candidate is $\text{CF}_3\text{I}$ gas. $\text{SF}_6$ and $\text{CF}_3\text{I}$ have a number of similar properties: both gases are colourless, odourless and non-flammable. The weak chemical bond $\text{C-I}$ in $\text{CF}_3\text{I}$ means that it can be decomposed quickly in the atmosphere, and therefore the ozone depletion potential of $\text{CF}_3\text{I}$ for surface release is less than 0.0001 [2]. In this way, $\text{CF}_3\text{I}$ is considered to be an environmentally friendly replacement to $\text{SF}_6$. However, $\text{CF}_3\text{I}$ has a high boiling point of $-22.5^\circ\text{C}$ at atmospheric pressure, as reported in [3]. This makes the use of pure $\text{CF}_3\text{I}$ less applicable for HV GIS/GIL equipment, which is normally pressurised at above 0.5 MPa. When considering $\text{CF}_3\text{I}$ as an alternative to $\text{SF}_6$, it is important to take into account that switchgear operated on the MV (11 kV) network uses $\text{SF}_6$ at a very low pressure (just above atmospheric pressure). For this reason, $\text{CF}_3\text{I}$ could be considered as a potential replacement candidate.

This paper provides an overview of the research work that has been conducted on $\text{CF}_3\text{I}$ gas at Cardiff University. In the paper, we present the results of the experimental investigations carried out on $\text{CF}_3\text{I}$-$\text{CO}_2$ mixtures of 30:70% including a) a comparison of properties between $\text{SF}_6$ and $\text{CF}_3\text{I}$ mixture, b) breakdown results obtained on rod-plane and plane-plane configurations filled with $\text{CF}_3\text{I}$-$\text{CO}_2$ mixtures; c) laboratory performance results of industrial switchgear designed for $\text{SF}_6$ gas when the gas is replaced with $\text{CF}_3\text{I}$ mixtures; d) a new scaled coaxial test rig to explore dielectric properties of gas insulated lines (GIL) using $\text{CF}_3\text{I}$ gas, and e) power systems studies investigating the performance of $\text{CF}_3\text{I}$ GIL for long distance transmission.

2. Comparison of Properties of $\text{SF}_6$ and $\text{CF}_3\text{I}$ Mixtures

Partial pressure of $\text{CF}_3\text{I}$ in the mixture is selected by a trade-off between three basic factors; boiling point of the gas mixture, insulation strength, and the by-products of the gas mixture upon each electrical discharge.

2.1 Saturation Vapour Pressure

Typically, in a GIL system, $\text{SF}_6$ gas is pressurised at 0.7 MPa. It can be seen from Figure 1 that the boiling point of $\text{CF}_3\text{I}$ at 0.7 MPa is 38°C, an indication that a buffer gas such as carbon dioxide ($\text{CO}_2$) needs to be added to $\text{CF}_3\text{I}$ in order to reduce the boiling temperature.

![Figure 1: Saturation vapour pressure curve of $\text{SF}_6$, $\text{CF}_3\text{I}$, $\text{CO}_2$ and 30:70% $\text{CF}_3\text{I}$-$\text{CO}_2$ mixture.](image)

2.2 Ionisation Coefficients

Effective ionisation coefficients of different gases and gas mixtures were computed using Bolsig+ software which applies the two-term approximation of Boltzmann equation [4]. Figure 2 shows the
pressure-reduced ionisation coefficient \((\alpha - \eta) / \rho\) as a function of \(E / \rho\) for different pure gases and CF\(_3\)I mixtures. It can be seen from Figure 2 that the critical reduced field strength at which \((\alpha - \eta) = 0\) for CF\(_3\)I is 108 kV/cm bar compared to 89 kV/cm bar in SF\(_6\) [5]. This is consistent with results reported in [6] which indicate that pure CF\(_3\)I has a dielectric strength of around 1.2 times higher than that SF\(_6\).

![Effective ionisation coefficients in pure gases (Air, SF\(_6\), CF\(_3\)I and CO\(_2\)) and CF\(_3\)I-CO\(_2\) mixtures (10%-90%, 20%-80% and 30:70%)](chart)

Figure 2 shows that 30:70% mixture ratio has a higher reduced field strength \(E / \rho\) compared to CF\(_3\)I-CO\(_2\) mixtures with low CF\(_3\)I contents. The 30:70% mixture ratio is considered to be most appropriate for gas-insulated switchgear (GIS) applications according to Katagiri et al. [7]. Kasuya et al. [8] suggested the same ratio for gas circuit breaker (GCB) applications. According to Katagiri et al. [7], for the same ratio, the interruption capability of CF\(_3\)I-CO\(_2\) mixtures is far superior to that of CF\(_3\)I-N\(_2\) mixtures. With only 30% of CF\(_3\)I in the CF\(_3\)I-CO\(_2\) mixture, the insulation performance was reported to be approximately 0.75 to 0.80 times that of SF\(_6\). The 30:70% mixture ratio, therefore, offers a reasonably high dielectric strength while being able to sustain its gaseous form at 0.7 MPa with a boiling temperature of mixture of around –4°C. Furthermore, by-products produced during arcing such as iodine can be reduced substantially using 30:70% mixture, which is indicated in another paper by Kasuya et al. [1]. It is important to minimise iodine deposition as it can compromise CF\(_3\)I insulation performance, as reported by Takeda et al. [9].

### 3. Breakdown Strength under Rod-plane and Plane-plane Configurations

To characterise the 30:70% CF\(_3\)I-CO\(_2\) mixture as an insulation medium, lightning impulse experiments with both polarities were conducted on two electrode configurations, as shown in Figure 3. The up and down method [10] was used to determine the 50% breakdown voltage \((U_{50})\), and using this value, simulations were carried out using COMSOL to obtain the equivalent maximum electric field \((E_{max})\) at the breakdown voltage.

![Electrode configurations](diagram)

Figure 3: a) Rod-plane and b) Plane-plane electrode configurations
The field utilisation factor, $\eta$, was calculated using Equation (1). This is expressed as an approximate index of field uniformity of the electrode geometry, where a higher field utilisation factor represents a more uniform electric field configuration. ‘$g$’ represents the gap length between the HV and earth electrodes.

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}}$$

Where

$$E_{\text{mean}} = \frac{U_{50}}{g}$$

(2)

### 3.1 Rod-plane Electrode Configuration

In this test, a rod-plane electrode configuration has been chosen to represent very non-uniform electric field behaviour as shown in Figure 3a, and the results are shown in Figure 4. For a 1 cm gap, the $U_{50}$ of the CF$_3$I gas mixture is the same for both lightning impulse polarities. When the gap length is increased, $U_{50}$ for both impulse polarities also increases. The field utilisation factor, however, decreases as the gap length is increased which indicates higher non-uniformity. Under negative impulse, the increment in $U_{50}$ is more significant compared to that under positive impulse. At 5 cm and under negative impulse, $U_{50}$ has increased to almost 3 times compared with $U_{50}$ at 1 cm. Meanwhile, under positive impulse, the increment is about 1.8 times.

![Figure 4: $U_{50}$ and $E_{\text{max}}$ curve for 30:70% CF$_3$I-CO$_2$ gas mixture in a rod-plane electrode configuration under positive and negative lightning impulses](image)

Generally, it can be said that for the rod-plane electrode configuration, the $U_{50}$ voltage under a negative impulse voltage is higher than $U_{50}$ under a positive impulse voltage, similar to observations in air gaps. As discussed by Loeb and Kip [11], breakdown in the rod-plane electrode is due to the streamers. In negative streamers, the space charge build-up impedes the negative avalanche, while the space charge in positive streamers propagates toward the cathode. Due to this process, negative streamers require higher electric fields (and therefore higher breakdown voltages) than positive streamers [12] to obtain full breakdown of the gap.

### 3.2 Plane-plane Electrode Configuration

In the plane-plane electrode configuration shown in Figure 3b, it is expected that higher voltages are required in order for the CF$_3$I-CO$_2$ gas mixtures to achieve breakdown, when compared to a similar gap length configuration of the rod-plane configuration. It was essential, therefore, to limit the gap length such that the applied voltage is restricted for the safety of HV bushing in the experimental setup. For this reason, the gap length in this test is limited to 3 cm. Results for $U_{50}$ and $E_{\text{max}}$ under positive and negative impulse are plotted in relation to gap length, as shown in Figure 5.

The results in Figure 5 show a behaviour that is opposite from which was observed in the rod-plane configuration. In this plane-plane configuration, $U_{50}$ under positive impulse is higher than under negative impulse. With a 1 cm gap, there is only a 3% difference between both polarities, and the
observed voltage difference increases with gap length, 12.7% and 29% for 2 cm and 3 cm gaps respectively. Also, in this study, $U_{50}$ can be seen to increase quite linearly with gap length in a plane-plane configuration, up to 3 cm. Under positive impulse, $U_{50}$ increased to 2.8 times from a 1 cm gap to a 3 cm gap, and under negative impulse, the increment is approximately 2.4 times.

The trends in $U_{50}$ curves reflect the behaviour in $E_{\text{max}}$ curves, as can be seen in Figure 5. $E_{\text{max}}$ is observed to increase linearly with gap length, although the increment is not as much as for $U_{50}$. For $E_{\text{max}}$, the increment from a 1 cm to 3 cm gap is 1.56 times that under a positive impulse and just 1.3 times under a negative impulse.

Figure 5: $U_{50}$ and $E_{\text{max}}$ curve for 30:70% CF$_3$I-CO$_2$ gas mixture in plane-plane electrode configuration under positive and negative lightning impulses

4. Switchgear Application

To trial the application of a 30:70% CF$_3$I-CO$_2$ mixture in switchgear, an existing commercial Ring Main Unit (RMU) normally filled with SF$_6$ was tested using the CF$_3$I mixture. The RMU comprises two low-current ‘ring’ switches and a tee-off vacuum circuit breaker contained within a common gas insulated chamber as shown in Figure 6. Figure 6a shows the test setup for one of the low-current switches while Figure 6b shows the test arrangement for the vacuum circuit breaker. A mixture of 30:70% CF$_3$I-CO$_2$ was used at the rated filling pressure of the RMU of 0.14 MPa (abs.) for all the tests.

The RMU filled with standard SF$_6$ gas has a rated impulse withstand voltage of 75 kV. The RMU was subjected to the withstand voltage test outlined in procedure B in BS60060-1, which has been adapted
for switchgear and controlgear as set out in BS62271-1 [13] for impulse testing. Positive lightning impulses were applied to each phase in turn at a constant 75 kV. For the switches, one set of 25 impulses was applied to each phase to test the insulating withstand strength of the CF$_3$I-CO$_2$ gas mixture. For the vacuum circuit breakers, insulated by the CF$_3$I-CO$_2$ gas, two sets of impulses were applied to each phase of the RMU (a total of 50 impulses) to test the withstand strength of the gas mixture. The current transformer was used to identify a gas breakdown across the equipment.

The results of the test shown in Table 1 suggest that when the RMU is filled with an insulating gas mixture of 30:70% CF$_3$I-CO$_2$ no disruptive discharges are identified, either i) across the ring switch gas gap in a 25 impulse set or ii) across the vacuum circuit breaker in the 50 impulse set.

Table 1: 30:70% CF$_3$I-CO$_2$ RMU for 75 kV Positive Lightning Impulse Withstand Voltage tests

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>RMU Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Result</td>
<td>No. of gas breakdowns</td>
<td>Result</td>
<td>No. of gas breakdowns</td>
</tr>
<tr>
<td>Ring Switch</td>
<td>PASS</td>
<td>0/25</td>
<td>PASS</td>
<td>0/25</td>
</tr>
<tr>
<td>Circuit Breaker</td>
<td>PASS</td>
<td>0/50</td>
<td>PASS</td>
<td>0/50</td>
</tr>
</tbody>
</table>

The results in Table 1 suggest that the 30:70% CF$_3$I-CO$_2$ mixture can be a potential replacement for SF$_6$ in 11 kV switchgear. The current interruption capability of the 30:70% mixture has not been tested and, therefore, further work is required to establish whether the gas mixture could be used to insulate the ring switches.

5. Feasibility Study of GIL Using CF$_3$I Mixtures

The experiment using 30:70% CF$_3$I-CO$_2$ mixture described in Sections 3 and 4 show promising potential for gas insulation. Research using this same gas mixture was extended to a small-scale coaxial prototype system with the aim to explore the feasibility of replacing SF$_6$ in GIL/GIS systems.

5.1 Testing a Coaxial-GIL Model

The maximum electric field in a coaxial geometry is described by the following equation:

$$E_{max} = \frac{V_{applied}}{a \ln \left( \frac{b}{a} \right)}$$

Where ‘a’ is the conductor radius and ‘b’ represents the inner enclosure radius.

For a typical 400kV GIL geometry [14] having an inner conductor of radius 9 cm and outer enclosure with inner radius 24 cm, the maximum electric field at the inner conductor surface when the maximum lightning withstand voltage level is applied is

$$E_{max} = \frac{1425 \times 10^3}{9 \times \ln \left( \frac{24}{9} \right)} = 161.4 \text{ kV/cm}$$

To develop a laboratory scaled model, the design of the test geometry aimed to generate a similar maximum electric field within the voltage levels that can be applied to the test vessel. The selection of the dimensions ‘a’ and ‘b’ were based on practical constraints of fitting a small-scale coaxial system prototype inside the test vessel and voltage limitation of the HV bushing (approximately 85 kV). Another factor that need to be taken into consideration is the optimisation of the quantity log(b/a), for which a value of 1 is considered the optimal ratio [15] for gap distance and field uniformity inside a coaxial system. Using this approach, the nearest practical values of a and b were adopted giving a = 0.556 cm and b = 1.425 cm. Applying the dimensions of the scaled down coaxial system into Equation
similar maximum electric field strength to that of the full GIL was achieved with a $V_{\text{applied}}$ of 85 kV. The dimensions of the small-scale coaxial system were then used to design a simulation model as shown in Figure 7. As can be seen from the figure, the middle section is an aluminium metal enclosure with an aluminium conductor inside. The two end insulators have circular shaped holes to allow gas circulation inside the test vessel.

$$E_{\text{max}} = \frac{85 \times 10^3}{0.556 \times \ln \left( \frac{1.425}{0.556} \right)} = 162.4 \text{ kV/cm}$$

Detailed numerical simulations of the coaxial model were used to identify high electric stress regions. For the Coulomb simulations, the voltage on the conductor was set to 85 kV and the enclosure was grounded. As expected, the maximum electric field was found at the centre region of the conductor ($E_{\text{max}}$ 163 kV/cm). There are also high electric field regions on the edges of the enclosure. These high stress regions were alleviated by adding two grading rings at the edges of the enclosure as shown in Figure 8.

The refined fabricated model of the coaxial test system is shown in Figure 9a. The enclosure and conductor are both made out of aluminium metal, and a metal strip was welded onto one of the grading rings to make an earth connection. On the tip of the conductor there is 10 mm thread that is used for attaching the coaxial model onto a HV bushing inside the pressure vessel. The full setup of the experiment can be seen in Figure 9b. The lightning impulse was applied through the HV bushing and onto the test object. The up and down method was also used to determine $U_{50}$ in this experiment. The tests were conducted with increasing pressure from 0.05 to 0.3 MPa (abs.).

The results are displayed in Figure 10 and, as expected, $U_{50}$ increases against increasing pressure. At 0.2 MPa (abs.), the measured $U_{50}$ is around 84 kV which is nearly the same as the terminal voltage of 85 kV that was initially calculated. Tests were also conducted for air at 0.2 MPa (abs.), and the measured $U_{50}$ was 38 kV which makes 30:70% CF$_3$I-CO$_2$ mixture is 2.2 times higher than air under similar conditions. For a GIL system, it is important to minimise the occurrence of gas discharge. To do this, the withstand strength need be designed lower than the critical reduced field strength of whichever CF$_3$I mixture to be used as the insulation medium.
5.2 Simulation Study of 400kV GIL System for Long Transmission of Bulk Power

An EMTP-ATP model shown in Figure 11 has been developed based on the geometric and the material properties of a typical 400 kV SF₆ GIL system [14] to study the characteristics of a GIL as a long transmission system. The purpose of this simulation is to determine the transmission capacity limit without reactive power compensation. The model is represented by three phase single core line and divided into six 50 km sections. The voltage drop limit should be within ±5%. The simulation shows that this was reached at 800 km length and 90% of the transmitted power was reached at 670 km. This indicates a low power loss over long distance transmission for a GIL system. The maximum transmitted power versus line length can be limited by factors such as reactive power generated by the shunt capacitance, load condition and operation power factor. The power factor and load condition was set as 0.8 and 100%, respectively, which was achieved by load regulation at the receiving end. Voltage profiles for different line lengths, ranging from 200 to 500 km, are shown in Figure 12b. As can be seen, the voltage drop at 200 km is 11%, and this is increased to 23.5% at 500 km under full load conditions.
Further simulations were conducted to analyse the change in voltage at different load conditions and power factors. For a line length of 300 km, load conditions ranging from 0% to 120% were studied using 0.8 power factor. The drop in voltage for 0% load condition is 5.44%, and this changed to –0.4% for 120% load condition, as shown in Figure 13a. It can be seen from Figure 13b that the power factor was adjusted to analyse the change in voltage profile with 100% load condition maintained. The voltage drop at unity power factor is –1.2%. When the power factor was adjusted from unity to 0.8 lagging, the voltage drop is increased to –15.45%. On the other hand, when the power factor was changed from unity to 0.8 leading, the voltage drop is around 14%. The simulation results show that utilizing GIL as a transmission system up to 300 km is possible with ±0.98 power factor and 100% load condition without reactive power compensation.

### 6. Conclusion

This paper discussed the work carried out on CF$_3$I mixture and its potential to replace SF$_6$ in high-voltage equipment. 50% breakdown tests conducted on three electrode configurations (rod-plane, plane-plane and coaxial) were used to characterise 30:70% mixture of CF$_3$I-CO$_2$. The breakdown strength of the mixture for coaxial electrode was more than two times higher than air. In comparison, breakdown strength of pure SF$_6$ is about three times higher than air. The insulation capability makes CF$_3$I a feasible alternative to SF$_6$ in a GIL system where arc quenching is not required. On the other hand, iodine deposition after every electrical discharge means CF$_3$I mixture may not be a suitable arc quenching gas for GIS applications that require high current interruption. However, the withstand tests on the RMU suggest CF$_3$I mixture may potentially be used in MV switchgear. The high boiling point of pure CF$_3$I means only low percentage of CF$_3$I content can be used in a gas mixture. More tests will be conducted on other CF$_3$I-CO$_2$ mixture ratios (20:80% and 10:90%) and CF$_3$I mixture with N$_2$ gas. This future work will be focussed on investigating CF$_3$I properties as an insulation medium.

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