



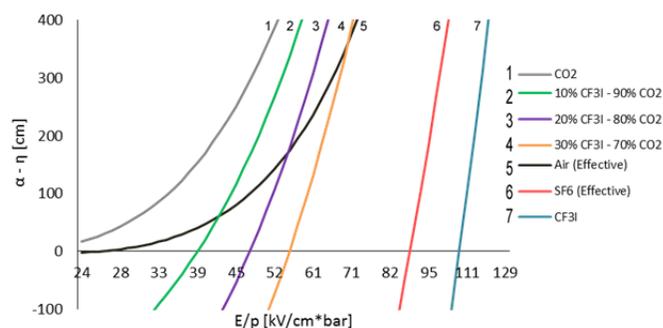
and only insulates the equipment such as around vacuum circuit breakers is a promising prospect. In this investigation, a Ring Main Unit (RMU) with vacuum interrupters have been insulated with a  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixture and then subjected to a number of tests to investigate the insulation properties and the suitability of the proposed gas mixture as a replacement to the currently-used  $\text{SF}_6$  gas.

## 2 PROPERTIES OF PURE $\text{CF}_3\text{I}$ AND $\text{CF}_3\text{I}$ - $\text{CO}_2$ GAS MIXTURES

Initially, to introduce  $\text{CF}_3\text{I}$  gas as a direct insulation alternative to  $\text{SF}_6$ , it is appropriate to view the available properties of  $\text{CF}_3\text{I}$  against those of  $\text{SF}_6$ , as shown in Table 1. As can be observed on the table,  $\text{CF}_3\text{I}$  has a significantly lower atmospheric lifetime and global warming potential than  $\text{SF}_6$ . However, the high boiling point of  $\text{CF}_3\text{I}$ , against that of  $\text{SF}_6$ , may cause a problem when this gas is used in future HV applications where a gas chambers pressure is increased. This required high pressure could be eliminated by the use of a gas mixture with a buffer gas such as  $\text{CO}_2$ . However, it is important that the dielectric strength of the resulting  $\text{CF}_3\text{I}$  gas mixture is maintained. In this paper, low overpressure MV switchgear is used so that the boiling point is not an issue. However, to reduce cost and to trial future applications, a mixture of  $\text{CF}_3\text{I}$ - $\text{CO}_2$  is proposed. The toxicity of  $\text{CF}_3\text{I}$  as an alternative gas is reduced as the amount of buffer gas ( $\text{CO}_2$ ) is increased in the gas mixture. Both of these gases are non-flammable and non-ozone depleting.

It can be shown that the use of  $\text{CF}_3\text{I}$  as an alternative to  $\text{SF}_6$  could be realised provided the correct mixture ratio of  $\text{CF}_3\text{I}$

but lowers the boiling point when compared with pure  $\text{CF}_3\text{I}$  and reduces the by-products produced during electrical arcing in the gas. For the case of  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixtures, parameters of the dielectric strength have been evaluated using the BOLSIG+ software, which use Boltzmann equation to quantify the pressure-reduced effective ionisation coefficients of different  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixtures, as shown in Figure 1 [7].



**Figure 1.** Effective ionisation coefficients in pure gases (Air,  $\text{SF}_6$ ,  $\text{CF}_3\text{I}$  and  $\text{CO}_2$ ) and  $\text{CF}_3\text{I}$ - $\text{CO}_2$  mixtures (10%-90%, 20%-80% and 30%-70%).

It can be seen from Figure 1 that the critical reduced electric field strength of pure  $\text{CF}_3\text{I}$  is 108 kV/cm bar compared to 89 kV/cm bar in  $\text{SF}_6$ . This confirms the previous findings of practical experimental research which showed that 100%  $\text{CF}_3\text{I}$  has a dielectric strength 1.2 times that of  $\text{SF}_6$  and, therefore, validates the calculations performed on gas mixtures [5]. Figure 1 also shows that, of all the  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixtures that have been analysed, the highest critical reduced electric field strength was found to correspond to gas mixture 30:70%  $\text{CF}_3\text{I}$ - $\text{CO}_2$ . This indicated that a 30:70%  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixture was a front runner candidate replacement gas to trial in practical high voltage equipment.

Previous experimental investigations have also shown that a promising  $U_{50}$  breakdown strength of 30:70%  $\text{CF}_3\text{I}$ - $\text{CO}_2$  gas mixture was exhibited in a plane-plane configuration under both positive and negative lightning impulses, as reproduced in Figure 2 [7]. The breakdown strength of the gas mixture is expected to be significantly lower when used inside operational switchgear geometries, where non-uniform field distributions are frequently encountered.

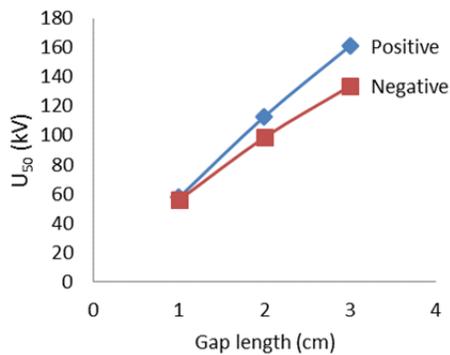
## 3 ESTIMATED WORLDWIDE LEAKAGE OF $\text{SF}_6$ GAS

The continued use of  $\text{SF}_6$  gas as an insulation medium worldwide is predicted to have a significant effect on the environment due to its high global warming potential and long atmospheric lifetime. This is based on rough estimates of the amounts of gas released into atmosphere through leakage from sealed systems as well as accidental gas escape. In order to quantify the amount of  $\text{SF}_6$  released into the atmosphere a study was carried out to estimate the total leakage of  $\text{SF}_6$  equipment.

**Table 1.** Comparison of properties for  $\text{CF}_3\text{I}$  and  $\text{SF}_6$  gases [2-7].

	$\text{SF}_6$	$\text{CF}_3\text{I}$
Name	Sulphur Hexafluoride	Trifluoroiodomethane
Molecular Weight (g/mol)	146.055	195.910
Boiling Point ( $^{\circ}\text{C}$ )	-63.9	-22.5
Atmospheric Lifetime	3200 Years	< 2 days
Ozone Depletion Potential (ODP)	0	0.008
Global Warming Potential (GWP)	23,500	< 5
By-Products	$\text{CF}_4$ , $\text{SiF}_4$ , $\text{SO}_2\text{F}_2$ , $\text{SOF}_4$ , $\text{SOF}_2$ and $\text{SO}_2$	Iodine, $\text{C}_2\text{F}_6$ , $\text{C}_2\text{F}_4$ and $\text{C}_3\text{F}_5\text{I}$
Exposure Guidelines (Toxicity)	Non toxic in pure state, toxicity increases once by-products are formed from arcing.	Iodine is formed from arcing, possible mutagenic.
Dielectric Strength compared to $\text{SF}_6$	1	1.2

with a suitable buffer gas, such as  $\text{N}_2$  or  $\text{CO}_2$ , is carefully selected. The use of a gas mixture, such as 30%-70%  $\text{CF}_3\text{I}$ - $\text{CO}_2$ , is a compromise which reduces the dielectric strength



**Figure 2.**  $U_{50}$  curve for 30:70%  $CF_3I-CO_2$  gas mixture in plane-plane electrode configuration under positive and negative lightning impulses [7].

A conservative gas proportion of 0.1% leakage rate per year [8] is adopted to evaluate the total gas released into the atmosphere and obtain realistic estimations, as specified by IEC 62271-1 for  $SF_6$  equipment to fulfil the requirements for sealed pressure systems. It is noted that the leakage rate per year may be less or more than the value used but it is often dependent on the age and degradation stage of the equipment. The calculations are performed over a representative high voltage equipment lifetime of 25 years with a 0.1% leakage rate without gas replacement each year. These estimates do not include leakage from gas handling operations or gas chamber containment failures due to design/manufacturing weaknesses or accidental damage.

The estimated leakage of  $SF_6$  gas from power systems medium voltage (MV) equipment employed worldwide over a 25 year lifetime is shown in Table 2 [9]. The same estimated  $SF_6$  leakage from high voltage (HV) equipment is shown in Table 3 [9].

For each of the calculated results, an equivalent ratio of  $CO_2$  emissions can be estimated. It can be estimated that for every 1 kg of  $SF_6$  released into the atmosphere, it is equivalent to

**Table 2.** Estimated leakage of MV  $SF_6$  Ring Main Units (RMU's), circuit breakers (CB's) and switches employed worldwide.

Total No. of MV $SF_6$ Insulated RMU's	2,322,600
Total No. of MV $SF_6$ Insulated CB's	500,000
Total No. of MV $SF_6$ Insulated Switches	677,400
Total Amount of $SF_6$ employed in all MV RMU's, CB's & Switches	1,834,164 kg
Yearly leakage of $SF_6$ from all MV RMU's, CB's & Switches	1,812 kg
25 Year leakage of $SF_6$ from all MV RMU's, CB's & Switches	45,308 kg

**Table 3.** Estimated leakage of HV  $SF_6$  gas insulated switchgear (GIS), open type circuit breakers (CB's) and gas insulated lines (GIL) employed worldwide.

Total No. of $SF_6$ Insulated GIS	20,000
Total No. of $SF_6$ Insulated Open Type CBs	100,000
Total No. of $SF_6$ Insulated GIL (m)	30,000
Total Amount of $SF_6$ employed in all HV GIS, Open Type CB's & GIL	15,907,184 kg
Yearly leakage of $SF_6$ from all HV GIS, Open Type CB's & GIL	15,717 kg
25 Year leakage of $SF_6$ from all HV GIS, Open Type CB's & GIL	392,944 kg

23,900 kg of  $CO_2$  being released. From Table 2, it can be estimated that the worldwide leakage from all MV  $SF_6$  equipment over a 25 year period is approximately 45 tons, this equipment is similar to that investigated throughout this paper. From Tables 2 and 3, the estimated worldwide leakage from all HV and MV equipment over a 25 year period is approximately 438 tons of  $SF_6$ . This is the equivalent to 10468 ktons of  $CO_2$ .

The potential problems are apparent when calculating the estimated  $SF_6$  leakage for equipment currently installed worldwide. This highlights the potential problem with gas equipment leaking and the estimated amount of gas that will be released into the atmosphere during the installed equipment's lifetime on the network. These amounts do not include any extra leakage from gas handling operations and equipment failures that may be significant. Although  $SF_6$  emissions are not as large as worldwide emissions of  $CO_2$ , the long lifetime of  $SF_6$  in the atmosphere makes its leakage a far reaching problem into the future.

## 4 TEST SETUP

This section presents the details of the test setup and provides a description of the ring main unit tested in the high voltage laboratory at Cardiff University. Further information is provided on the RMU testing configurations and the test circuit used to apply lightning impulses to the switchgear.

### 4.1 RING MAIN UNIT SPECIFICATIONS

In order to test the suitability of using vacuum current interrupters in conjunction with gas insulation in switchgear, a single circuit ring main unit (RMU) with interlocked cable test facility has been utilized as shown in Figure 3.

The ring main unit (RMU) is made up of two low current ring switches and a tee-off vacuum circuit breaker per phase contained within a common gas insulated chamber. The internal arrangement of the RMU is similar to another RMU, also developed by the same manufacturer, as shown in Figure 4.



**Figure 3.** Tested vacuum breaker (SCRMU Ring Main Unit) insulated with  $CF_3I-CO_2$  gas mixture.

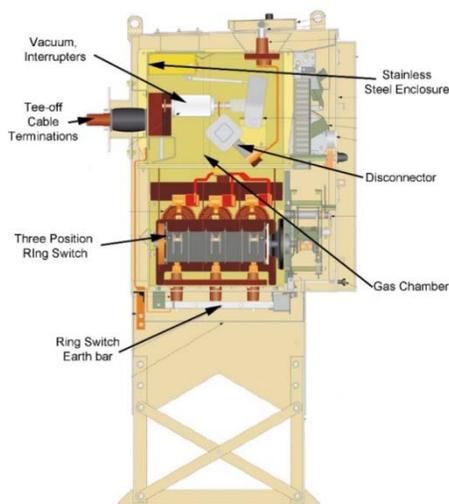


Figure 4. An internal view of similar RMU switchgear [10].

From the manufacturers’ specifications for the RMU, and as summarized in Table 4, it is important to note that the unit has a rated voltage of 11 kV. The RMU’s vacuum interrupters and its gas insulation is expected to withstand a standard lightning impulse of 75 kV at a normal operating pressure of 0.4 bar(g). The insulation gas in the common gas chamber, within the unit is expected to insulate two ring switches and a circuit breaker for each of the three phases. To operate this unit at the recommended pressure, 1.3 kg of SF<sub>6</sub> gas is required to fill the gas chamber.

The RMU gas chamber is designed so that it is one large chamber that houses all three phases of the vacuum circuit

Table 4. Key rated specifications of the tested vacuum switchgear RMU referring to standard SF<sub>6</sub> filling [11, 12].

Note: 0.4 bar(g) = 140 kPa = 0.14 MPa.

Unit Reference	RMU
Year of manufacture	2000
Weight	510 kg
Rated Voltage	11 kV
Frequency	50 Hz
Impulse withstand voltage	75 kV
Minimum gas pressure	0.05 bar(g) (20°C)
Filling pressure	0.4 bar(g) (20°C)
Weight of gas at filling pressure	1.3 kg
Minimum operating temperature	-25°C

	Ring switches	Circuit breaker
Normal current (A)	630	200
Short circuit peak making current (kA)	40	40
Short circuit breaking current (kA)	-	20
3 second short time current (kA)	16	16
Earth switch peak making current (kA)	40	40

breaker, as well as being the main insulating medium for all the switches. The lightning impulse withstand tests were conducted when the unit was filled with 30% CF<sub>3</sub>I mixed with 70% CO<sub>2</sub> to trial the applications of CF<sub>3</sub>I-CO<sub>2</sub> gas mixtures in switchgear. 30%:70% CF<sub>3</sub>I-CO<sub>2</sub> was chosen to insulate the equipment based on previous research which has shown promising insulation strength for this mixture ratio as well as a lower boiling point [4, 7]. The RMU was filled to the rated filling pressure of 0.4 bar(g). The contacts inside the switchgear remained unmodified throughout testing and were left as the equipment was manufactured. It is also worth highlighting that this unit was previously used on the UK network, and was in operation for approximately 12 years of service. Therefore, it is expected that the contacts within the switches and circuit breaker may have degraded since they were manufactured. This, however, does not affect the investigation described in this paper as it focusses on the insulation performance of the enclosing chamber and the dielectric properties of the insulating gas surrounding the vacuum bottles.

To fill the test RMU switchgear, the unit was first placed under vacuum by evacuating all remaining air from the gas chamber, using a Dilo Mini Series, as is normally carried out by the manufacturer when the unit was first installed in the electricity network. The RMU was then filled with new CF<sub>3</sub>I and CO<sub>2</sub> straight from their respective storage cylinders, to achieve a positive pressure inside the gas chamber of 0.4 bar(g).

#### 4.2 GAS PRESSURE-PRESSURE MIXTURE CALCULATION

In order to fill the ring main unit with the correct amount of CF<sub>3</sub>I and CO<sub>2</sub>, so that the correct pressure-pressure gas mixture ratio can be achieved, it was necessary to calculate the correct amount of gas needed. It is important to note that all gas mixtures are pressure-pressure ratios and not weight-weight mixture ratios, as the molecular weight of any molecule can greatly affect the pressure mixture. The total amount of CF<sub>3</sub>I and CO<sub>2</sub> needed to fill the RMU with 30%:70% CF<sub>3</sub>I-CO<sub>2</sub> to 0.4 bar(g) can be calculated using the ideal gas law principle as shown in Equation (1) [13].

$$V = \frac{mRT}{MW \times P} \tag{1}$$

Where:

m = mass of gas (grams), T = temperature (Kelvin),  
 P = pressure (bar), MW = molecular weight of gas (g mol<sup>-1</sup>),  
 R = ideal gas constant, V = volume (litres).

For SF<sub>6</sub> operation, the filling temperature is 20°C. The ideal gas constant (R) is 0.0821. The molecular weight (MW) of SF<sub>6</sub> is 146.0554192 g mol<sup>-1</sup>, the MW of CF<sub>3</sub>I is 195.9104 g mol<sup>-1</sup> and MW of CO<sub>2</sub> = 44.01 g mol<sup>-1</sup>. Therefore, when the RMU is filled with pure SF<sub>6</sub>, the gas chamber volume can be calculated as follows [13]:

$$V = \frac{mRT}{MW \times P} = \frac{1300 \times 0.0821 \times 293.15}{146.0554192 \times 1.4} = 153.01 \text{ L} \quad (2)$$

In order to fill the RMU with 30% pressure of  $CF_3I$ , the ideal gas law can be rearranged to calculate the amount of  $CF_3I$  needed:

$$m = \frac{MW \times PV}{RT} = \frac{195.9104 \times 0.42 \times 153.01}{0.0821 \times 293.15} = 523.11 \text{ g} \quad (3)$$

To fill the RMU with 70% pressure of  $CO_2$ , the mass of  $CO_2$  needed is:

$$m = \frac{MW \times PV}{RT} = \frac{44.01 \times 0.98 \times 153.01}{0.0821 \times 293.15} = 274.20 \text{ g} \quad (4)$$

Therefore, the total amount of gas required to fill the RMU with 30%  $CF_3I$  and 70%  $CO_2$  is 523.11 g of  $CF_3I$  and 274.20 g of  $CO_2$ . This gives a gas mixture ratio, for 30%:70%  $CF_3I$ - $CO_2$ , of:

$$1.908 \text{ g} : 1 \text{ g} \quad CF_3I : CO_2$$

### 4.3 TEST CIRCUIT SETUP

Figure 5 shows the adopted laboratory test circuit set up for the lightning breakdown test programme. The test switchgear is connected to a lightning impulse generator and grounded as shown in the figure. The impulse generator used for the tests is capable of delivering up to 400 kV standard lightning impulses (1.2/50  $\mu$ s).

A capacitive impulse divider with a response time of 49 ns and a ratio of 27931 to 1 is used throughout the test programme. A digital storage oscilloscope (Lecroy Wave Jet 100 MHz) was used to store and examine the impulse shape. The adopted experimental set up allows obtaining a measured voltage within the required  $\pm 3\%$  of the intended applied voltage which conforms to the standard parameters specified in IEC 60060-1 [14].

A typical lightning impulse (1.2/50  $\mu$ s) record applied to the ring main unit is shown in Figure 6. In this particular test, the gas mixture, which surrounds the vacuum circuit breaker, is capable of withstanding the peak voltage of the lightning impulse which is measured to be 74.6 kV. If a breakdown had occurred across any parts of the circuit breaker or gas insulation, a sudden collapse in voltage would have been recorded, and the current measured on the grounding lead of the circuit breaker would exhibit a sharp and sudden increase at the same instant.

### 4.4 RMU STANDARD LIGHTNING IMPULSE WITHSTAND TESTS AND CONNECTIONS

The ring main unit under test was connected to the lightning impulse generator with associated controls and connections to various components are achieved as shown in Figure 7.

Standard lightning impulse (1.2/50) tests were conducted using the laboratory test set up and in accordance with the standard recommendations. The RMU has a rated impulse withstand voltage of 75 kV. In this investigation, the RMU was subjected to the withstand voltage tests as outlined in procedure B of BS60060-1 [14], which has been adapted for impulse testing of switchgear and control gear tests as described in BS62271-1 [8].

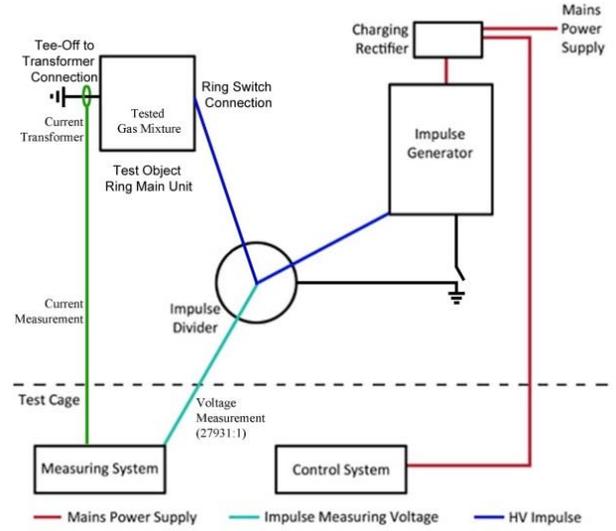


Figure 5. Lightning impulse test circuit setup.

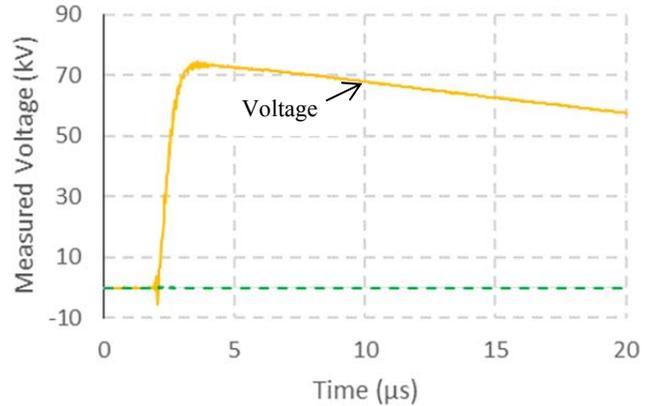


Figure 6. Applied lightning impulse voltage and zero current due to successful test measurement (dashed).

The basic impulse level (BIL) withstand test is designed to stress the insulation of switchgear by the repeated application of a very steep fronted voltage wave, and is a very searching test of the unit's insulation integrity. According to BS EN 62771-1, for  $U_r \leq 245$  kV, switchgear and control gear shall be subjected to lightning impulse voltages in dry conditions only [8]. For this test programme, positive lightning impulses were applied to each phase in turn, one after the other, at a constant 75 kV peak impulse voltage magnitude. Tests could not be applied above 75 kV due to the insulation strength of air bushings on the outside of the unit that could not prevent flashover to the earthed switchgear casing above this voltage. For the ring switches, a maximum 25-impulse series was

applied to each phase in order to determine the insulation withstand strength of the  $CF_3I-CO_2$  gas mixture. To evaluate the insulation strength of the open ring switches, the RMU was placed in the position shown in Figure 8. Current measurement using a current transformer was used to identify the gas electrical breakdown across any terminals of the tested equipment.

For the vacuum circuit breakers, insulated with  $CF_3I-CO_2$  gas, two maximum 25 impulse series of positive polarity were applied to each phase of the RMU (a total of 50 impulses) to examine the insulating withstand strength of the gas mixture.

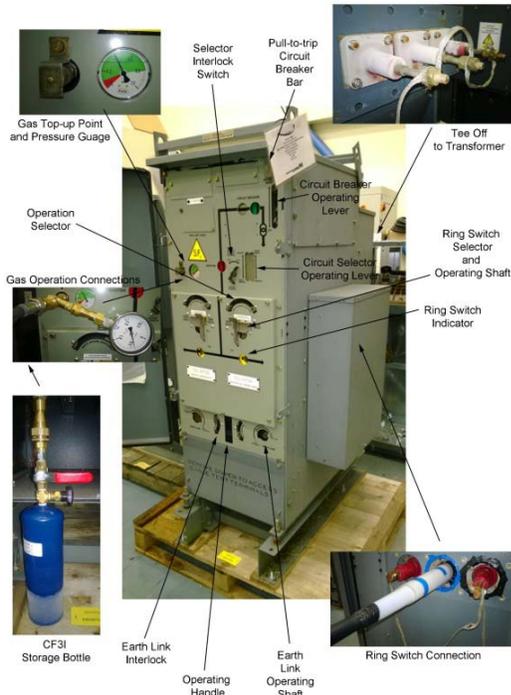


Figure 7. Connections and operational components of the RMU.

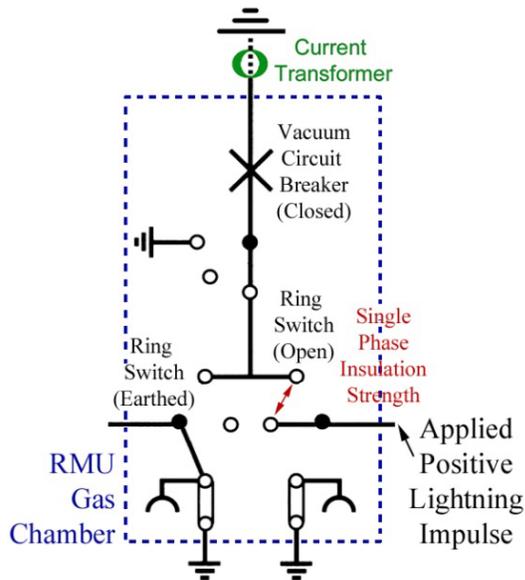


Figure 8. RMU single phase positive lightning impulse gas insulation test circuit for ring switches.

To test the insulation strength of the gas surrounding the vacuum circuit breaker interruption chamber, the RMU was

configured and connected as shown in the positions of Figure 9. Again, a current transformer was used to indicate whether a breakdown across the equipment had occurred during each test.

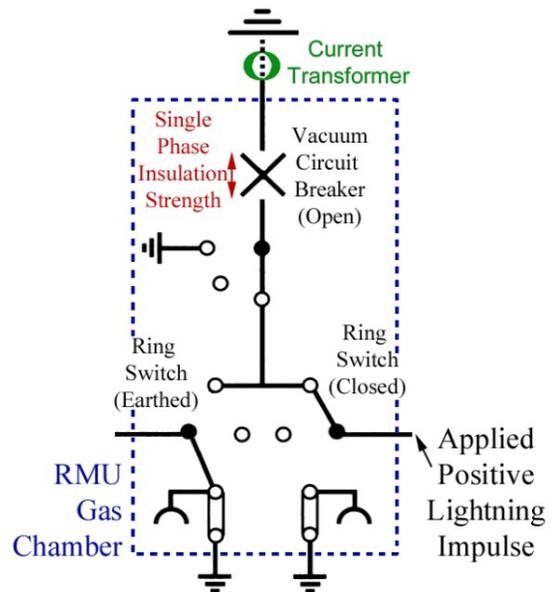


Figure 9. RMU single phase positive lightning impulse test circuit for vacuum circuit breakers surrounded by  $CF_3I-CO_2$  gas mixture insulation.

## 5 RMU LIGHTNING IMPULSE WITHSTAND TEST RESULTS

Under normal substation conditions, a ring main unit filled with  $SF_6$  would be expected to insulate against a 25 lightning impulse series with no more than 2 breakdown failures [8]. In this work, when the RMU was filled with an insulating gas mixture of 30%:70%  $CF_3I-CO_2$ , no disruptive discharges were detected across the ring switch gas gap during a test consisting of a 25 impulse series across each of the phases, as shown in Table 5.

Furthermore, it was found that when the RMU vacuum circuit breakers are insulated with a 30%:70%  $CF_3I-CO_2$  gas mixture, no disruptive discharges are detected across the vacuum circuit breakers for a 50 impulse test series, as shown in Table 6.

These results show that, overall, the average insulation strength of a ring vacuum switch insulated only with a  $CF_3I-CO_2$  gas mixture and the insulation strength of a vacuum circuit breaker insulated by  $CF_3I-CO_2$  is comparable to that of  $SF_6$  as summarized in Table 7

## 6 CONCLUSION

Investigations with 30%:70%  $CF_3I-CO_2$  gas mixture at 0.4 bar(g) and BIL test voltages of 75 kV show that the application in MV switchgear is promising and demonstrates an alternative high voltage insulation medium to  $SF_6$ . Furthermore, it could be a potential alternative insulation gas even for HV switchgear. These findings indicate the potential dielectric strength of the proposed gas mixture and

demonstrate that the performance of insulation gases can be measured in gas insulated switchgear.

It was found through extensive laboratory testing that, in the ring switches of the tested RMU, the insulation performance of the gas mixture is comparable to that of SF<sub>6</sub> in practical ‘complex’ switchgear contact configurations. As a result of this work, it can be concluded that the proposed mixture can fulfill the insulation duty in MV equipment and, in particular, around the tested vacuum circuit breakers. Additional tests planned in the future shall demonstrate the reliability of such mixture gases over longer period of application.

No tests were carried out to examine the current interruption capability for the gas mixture in circuit breaker applications. Previous work indicated that the use of this gas mixture is suitable for the interruption of low current up to around 100A. Future work will examine the practical limits of current interruption of the proposed gas.

### ACKNOWLEDGMENT

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**Table 5.** 30%:70% CF<sub>3</sub>I-CO<sub>2</sub> insulated RMU ring switch positive lightning impulse withstand voltage tests.

Ring switch phase	Result	Number of gas breakdowns
Phase 1	PASS	0/25
Phase 2	PASS	0/25
Phase 3	PASS	0/25

**Table 6.** 30%:70% CF<sub>3</sub>I-CO<sub>2</sub> insulated RMU vacuum circuit breaker positive lightning impulse withstand voltage tests.

Circuit breaker phase	Result	Number of breakdowns
Phase 1	PASS	0/50
Phase 2	PASS	0/50
Phase 3	PASS	0/50

**Table 7.** 30%:70% CF<sub>3</sub>I-CO<sub>2</sub> insulated RMU average for all 75 kV positive lightning impulse withstand voltage tests.

	Result	Number of breakdowns
CF <sub>3</sub> I-CO <sub>2</sub> Insulated Ring Switch	PASS	0/75
Vacuum Bottle / CF <sub>3</sub> I-CO <sub>2</sub> Insulated Circuit Breaker	PASS	0/150

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