Breakdown Performance of Vacuum Circuit Breakers Using Alternative CF_3I-CO_2 Insulation Gas Mixture

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ABSTRACT

In this paper, sulphur hexafluoride (SF_6) insulated vacuum interrupter circuit breakers have been used to explore replacing SF_6 gas with a trifluoroiodomethane and carbon dioxide (CF_3I-CO_2) gas mixture. The search for an alternative insulation gas is driven by the well known extreme global warming potential of SF_6. For this purpose, the circuit breaker gas compartment of a piece of gas insulated switchgear (GIS) was filled with a CF_3I gas mixture and then tested using lightning impulses up to the rated withstand strength. The tested ring main unit was initially designed to be insulated with SF_6 gas. The unit is a three-phase switchgear containing two switches per phase; a selector interlock and a vacuum bottle circuit breaker per phase. The test programme performed in this investigation demonstrated the breakdown performance and insulation strength of the new gas mixture as well as the vacuum circuit breakers behavior when insulated with a new insulation medium. Data on the dielectric properties of the proposed gas mixture is presented, and the performance of the tested vacuum circuit breaker is discussed. Promising results are obtained which indicate the suitability of this more-environmentally friendly gas for high voltage insulation purposes.

Index Terms — **Vacuum insulation, Vacuum circuit breakers, Gas insulated switchgear, SF_6, CF_3I-CO_2 gas mixture.**

1 INTRODUCTION

IN the power industry today, several designs and examples of medium voltage (MV) switchgear using vacuum bottles / interrupting technology can be found. The modern versions are often insulated with SF_6 gas [1]. However, from published literature, the global warming effect of SF_6 has become apparent, and it has been well documented that its global warming potential (GWP) is 23,900 times that of CO_2 [2]. SF_6 also has an atmospheric lifetime of 3,200 years, making it a potential environmental hazard when released into the atmosphere [3]. At present, significant research effort is focused on finding alternative insulation gases to SF_6, such as trifluoroiodomethane (CF_3I) and its mixtures with CO_2 and N_2. CF_3I has a high boiling point and is, therefore, used as part of a gas mixture as an insulation medium [4]. A gas mixture of CF_3I and CO_2 helps lower the boiling point of CF_3I whilst trying to maintain the inherent insulating strength of CF_3I. Previous research [5, 6, 7] has shown that, under uniform electric fields, pure CF_3I can have an insulation strength as high as 1.2 times that of SF_6. CF_3I gas mixtures provide a dielectric strength in the range between air and SF_6, depending on the amount of CF_3I used.

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Switchgear units, such as the type investigated in this test programme, are already installed in electrical networks around the world. They utilize vacuum technology for current interruption but use SF_6 gas insulating medium to insulate the equipment and withstand high voltage impulses that may appear around the vacuum bottle located inside the SF_6 gas compartment. This paper examines the potential of using CF_3I-CO_2 as a direct replacement to SF_6 in switchgear which utilizes vacuum technology.

From published literature, it has been reported [3] that CF_3I gas has limited capability for arc interruption when arc currents are higher than 100A. This low current interruption capability has been reportedly due to the by-products of CF_3I. The iodine, which disassociates itself from pure CF_3I during arcing, attaches onto the circuit breaker contact surfaces, and may lead to reduced insulation performance [5]. Therefore, the use of 30%-70% CF_3I-CO_2 has been suggested to negate this problem, which reduces the amount of pure CF_3I used. However, an absorbent still needs to be utilized to remove this effect entirely as it is currently unknown how long term iodine deposits reside on the contacts surface. Pure CO_2 cannot be used as a direct replacement for SF_6 at higher pressures without a mixture of CF_3I because the switchgear already installed on the network is not suitable for use with higher pressure than used throughout this paper.

The proposal to use a mixture CF_3I-CO_2 gas as a replacement in switchgear where it does not interrupt current

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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 CF_3I-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 SF_6 gas.

2 PROPERTIES OF PURE CF_3I AND CF_3I-CO_2 GAS MIXTURES

Initially, to introduce CF_3I gas as a direct insulation alternative to SF_6, it is appropriate to view the available properties of CF_3I against those of SF_6, as shown in Table 1. As can be observed on the table, CF_3I has a significantly lower atmospheric lifetime and global warming potential than SF_6. However, the high boiling point of CF_3I, against that of 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 CO_2. However, it is important that the dielectric strength of the resulting CF_3I 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 CF_3I-CO_2 is proposed. The toxicity of CF_3I as an alternative gas is reduced as the amount of buffer gas (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 CF_3I as an alternative to SF_6 could be realised provided the correct mixture ratio of CF_3I with a suitable buffer gas, such as N_2 or CO_2, is carefully selected. The use of a gas mixture, such as 30%-70% CF_3I-CO_2, is a compromise which reduces the dielectric strength but lowers the boiling point when compared with pure CF_3I and reduces the by-products produced during electrical arcing in the gas. For the case of CF_3I-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 CF_3I-CO_2 gas mixtures, as shown in Figure 1 [7].

Table 1. Comparison of properties for CF_3I and SF_6 gases [2-7].

	SF_6	CF_3I
Name	Sulphur Hexafluoride	Trifluoroiodomethane
Molecular Weight (g/mol)	146.055	195.910
Boiling Point (°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	CF_4, SiF_4, SO_2F_2, SOF_4, SOF_2 and SO_2	Iodine, C_2F_6, C_2F_4 and C_2F_5I
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 SF_6	1	1.2

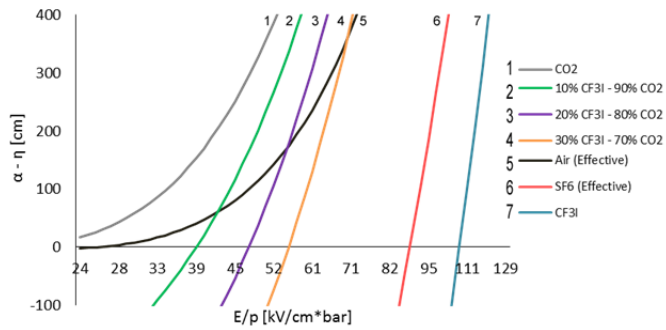

Figure 1. Effective ionisation coefficients in pure gases (Air, SF_6, CF_3I and CO_2) and CF_3I-CO_2 mixtures (10%-90%, 20%-80% and 30%-70%).

It can be seen from Figure 1 that the critical reduced electric field strength of pure CF_3I is 108 kV/cm bar compared to 89 kV/cm bar in SF_6. This confirms the previous findings of practical experimental research which showed that 100% CF_3I has a dielectric strength 1.2 times that of SF_6 and, therefore, validates the calculations preformed on gas mixtures [5]. Figure 1 also shows that, of all the CF_3I-CO_2 gas mixtures that have been analysed, the highest critical reduced electric field strength was found to correspond to gas mixture 30:70% CF_3I-CO_2. This indicated that a 30:70% CF_3I-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% CF_3I-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 SF6 GAS

The continued use of 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 SF_6 released into the atmosphere a study was carried out to estimate the total leakage of SF_6 equipment.

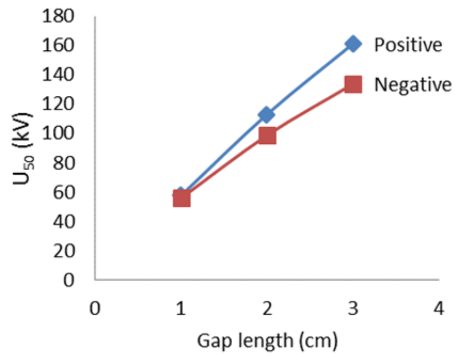

Figure 2. U_{50} curve for 30:70% CF_3I-CO_2 gas mixture in plane-plane electrode configuration under positive and negative lightning impulses [7].

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 preformed 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 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.

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 SF6 Insulated GIS	20,000
Total No. of SF6 Insulated Open Type CBs	100,000
Total No. of SF6 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

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.

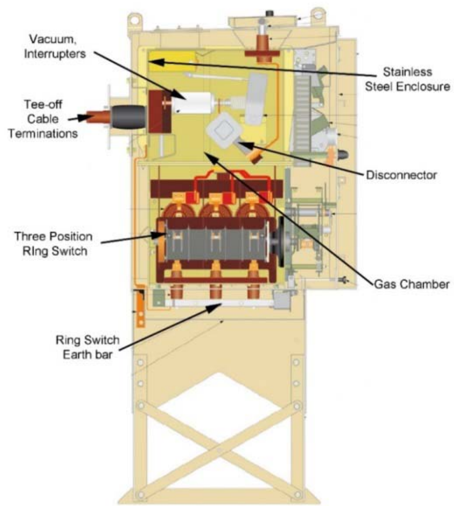

Figure 4. An internal view of similar RMU switchgear [10].

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_6 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 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_3I mixed with 70% CO_2 to trial the applications of CF_3I-CO_2 gas mixtures in switchgear. 30%:70% CF_3I-CO_2 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.

Table 4. Key rated specifications of the tested vacuum switchgear RMU referring to standard SF_6 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

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_3I and CO_2 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_3I and CO_2, 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_3I and CO_2 needed to fill the RMU with 30%:70% CF_3I-CO_2 to 0.4 bar(g) can be calculated using the ideal gas law principle as shown in Equation (1) [13].

$$V = \frac{mRT}{MW \times P} \qquad (1)$$

Where:
m = mass of gas (grams), T = temperature (Kelvin),
P = pressure (bar), MW = molecular weight of gas (g mol^{-1}),
R = ideal gas constant, V = volume (litres).

For SF_6 operation, the filling temperature is 20°C. The ideal gas constant (R) is 0.0821. The molecular weight (MW) of SF_6 is 146.0554192 g mol^{-1}, the MW of CF_3I is 195.9104 g mol^{-1} and MW of CO_2 = 44.01 g mol^{-1}. Therefore, when the RMU is filled with pure SF_6, the gas chamber volume can be calculated as follows [13]:

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

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:

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

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

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

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 g : 1 g $CF_3I : CO_2$

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 400 kV standard lightning impulses (1.2/50 µs).

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 ± 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 µs) 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].

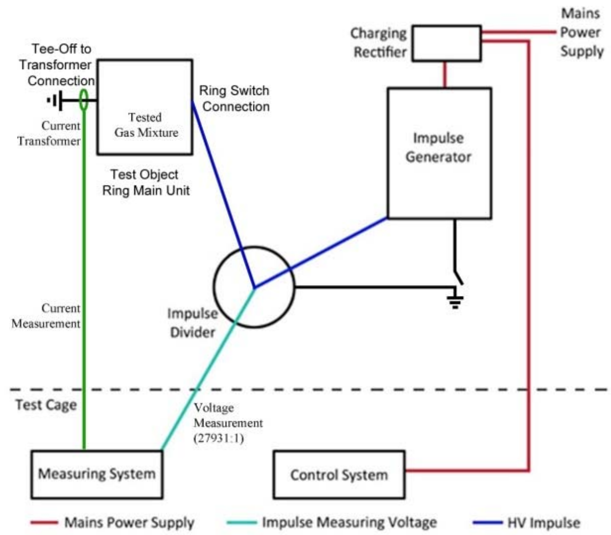

Figure 5. Lightning impulse test circuit setup.

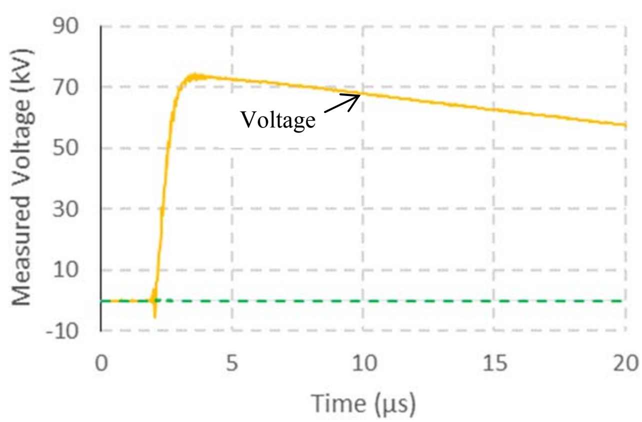

Figure 6. Applied lightning impulse voltage and zero current due to seccessful test measurement (dashed).

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.

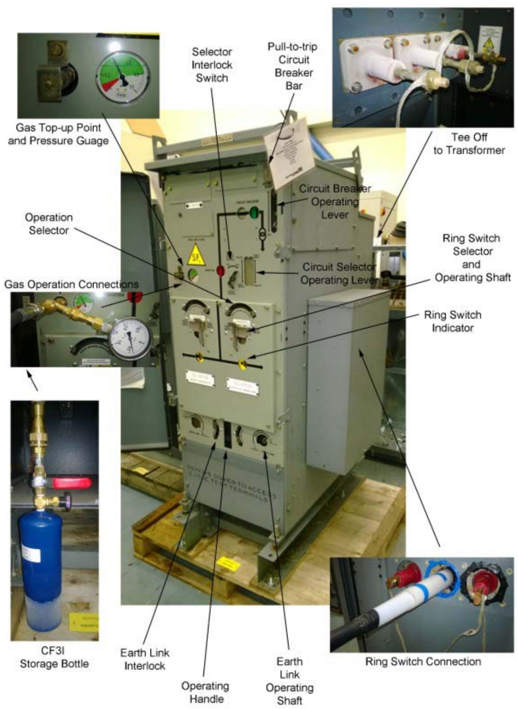

Figure 7. Connections and operational components of the RMU.

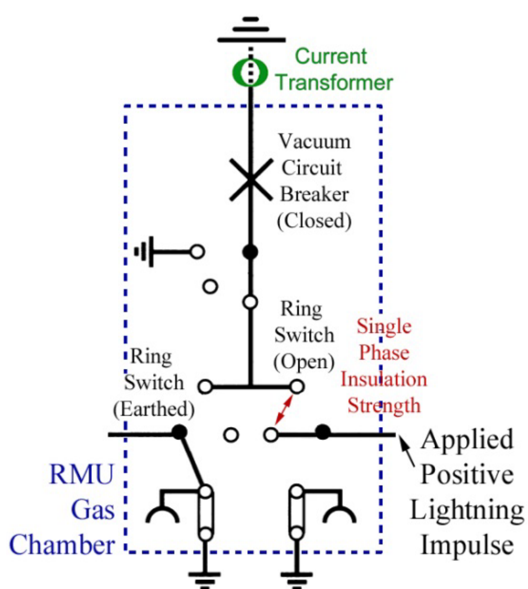

Figure 8. RMU single phase positive lightning impulse gas insulation test circuit for ring switches.

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.

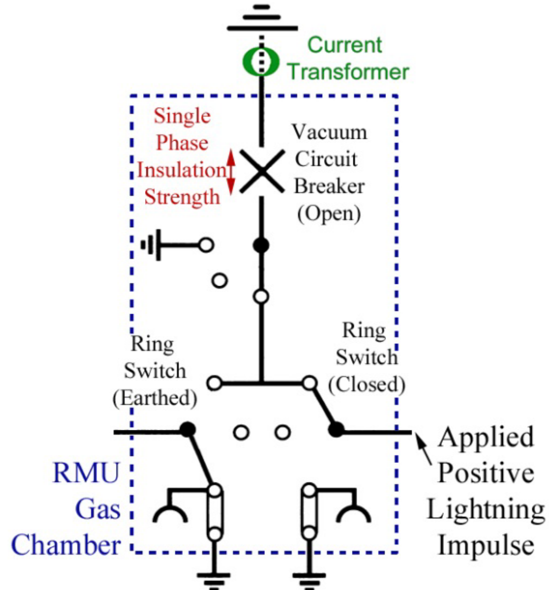

Figure 9. RMU single phase positive lightning impulse test circuit for vacuum circuit breakers surrounded by CF_3I-CO_2 gas mixture insulation.

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 breakdowns 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_6 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.

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Table 5. 30%:70% CF_3I-CO_2 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_3I-CO_2 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_3I-CO_2 insulated RMU average for all 75 kV positive lightning impulse withstand voltage tests.

	Result	Number of breakdowns
CF_3I-CO_2 Insulated Ring Switch	PASS	0/75
Vacuum Bottle / CF_3I-CO_2 Insulated Circuit Breaker	PASS	0/150

REFERENCES

[1] H. M. Ryan, "Circuit breakers and Interruption," in Advances in High Voltage Engineering, vol. 40, A. Haddad and D. Warne, Eds., London, IEE Power & Energy Series 40, The Institute of Electrical Engineers, pp. 415-476, 2004.

[2] Intergovernmental Panel on Climate Change (IPCC), Working Group I Contribution to Fourth Assessment Report of the IPCC - Intergovernmental Panel on Climate Change, Geneva, Switzerland: Addendum-Errata of Climate Change 2007 - The Physical Science Basis IPCC WG1 AR4 Report, 2008.

[3] H. Katagiri, H. Kasuya and S. Yanabu, "Measurement of Iodine Density Generated from CF_3I-CO_2 Mixture after Current Interruption," Japan-Korea Joint Symposium on Electrical Discharge and High Voltage Engineering, Shibaura Institute of Technology, Tokyo, 2007.

[4] H. Katagiri, H. Kasuya, H. Mizoguchi and S. Yanabu, "Investigation of the Performance of CF_3I Gas as a Possible Substitute for SF_6,", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, No. 5, pp. 1424 – 1429, 2008.

[5] T. Takeda, S. Matsuoka, A. Kumada and K. Hidaka, "Sparkover and Surface Flashover Charactersitics of CF_3I Gas under Application of Nanosecond Square Pulse Voltage," 16th Int'l. Sympos. High Voltage Eng. (ISH), Paper C-55, pp. 1-6, 2009.

[6] M.S. Kamarudin, M. Albano, P. Coventry, N. Harid and A. Haddad, "A survey on the potential of CF_3I gas as an alternative for SF_6 in high voltage applications,", 45th Int'l. Universities' Power Engineering Conf. (UPEC), Cardiff University, Wales, UK, 2010.

[7] M.S. Kamarudin, L. Chen, P. Widger, K.H. Elnaddab, M. Albano, H. Griffiths and A. Haddad, "CF_3I Gas and Its Mixtures: Potential for Electrical Insulation,", 45th Int'l. CIGRE Session' CIGRE, Paris, France, 2014.

[8] B. S. I. (BSI), "British Standard BS62271-1: High-voltage switchgear and controlgear - Part 1: Common specifications," 2008. [Online]. Available: www.bsigroup.com/standards. [Accessed 01 04 2014].

[9] P. Widger, *Investigation into CF_3I-CO_2 Gas Mixtures for Insulation of Gas-insulated Distribution Equipment*". PhD Thesis, Cardiff University, Wales, UK, 2014.

[10] Lucy Switchgear, "SABRE VRN6a SF6 RMU Automated distribution solutions - towards smarter electrical networks," Selangnor, Malysia: Lucy Switchgear, LS00001 SABRE VRN6a (Asia) 06 2013 9776, 2013. [Online]. Available: www.lucyswitchgear.com [Accessed 04 07 2013]

[11] Lucy Switchgear, SCRMU Instruction & Operation Manual Medium Voltage 12 -24 kV, Oxford: Lucy Switchgear, 1999.

[12] Lucy & Co. Ltd. Oxford., Lucy Swithgear SCRMU(M) Faceplate, Oxford: Lucy Switchgear, 2000.

[13] R. H. Petrucci, W. S. Harwood and F. G. Herring, *General Chemistry Principles and Modern Applications* (8th Edition), Eighth Edition, Upper Saddle River, New Jersey, New Jersey: Prentice-Hall Inc., ISBN 0-13-014329-4, 2002.

[14] British Standard Institution (BSI), "BS EN 60060-1: High-voltage test techniques Part 1: General definitions and test requirements," 2010. [Online]. Available: www.bsigroup.com/standards. [Accessed 01 04 2011].

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