BREAKDOWN CHARACTERISTICS OF CF_3I/CO_2 GAS MIXTURES UNDER FAST IMPULSE IN ROD-PLANE AND GIS GEOMETRIES

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Abstract: SF_6 is widely used in modern electricity transmission and distribution networks due to its outstanding dual qualities: arc quenching and dielectric insulation. As a gas medium, SF_6 is chemically inert, non-toxic and non-flammable, which makes possible the construction of compact SF_6 switchgear. However, the global warming potential over 100-yr for SF_6 gas is 23,900 times higher than CO_2. This has led to research into alternative gases with much lower environmental impact, and one of the emerging candidates is CF_3I gas and its mixtures. This paper describes collaborative work investigating the breakdown of a CF_3I/CO_2 gas mixture with a rod-plane configuration. The breakdown characteristics of 30/70% CF_3I/CO_2 gas mixture was experimentally determined using (i) a lightning impulse generator (1.2/50) and (ii) a steep-front impulse voltage generator (rise time of 16 ns). The test results show the breakdown voltage of the CF_3I/CO_2 gas mixture for different gap distances and gas pressures, and the V-t characteristics are presented in the range 20 ns to 20 µs. Furthermore, V-t characteristics are presented for a medium-voltage GIS unit, designed for SF_6 gas but tested with a 30/70% CF_3I/CO_2 gas mixture.

1 INTRODUCTION

SF_6 is a potent greenhouse gas with a 100-yr global warming potential (GWP) 23,900 times higher than CO_2 [1]. The use of SF_6 has not been banned in high-voltage applications because there is, as yet, no suitable commercially available alternative. However, there is a growing interest in developing gas-insulated systems which use less SF_6 or none at all. Consequently, a second generation of gas-insulated lines (GIL) was developed using a gas mixture ratio of 80% N_2 and 20% SF_6. CF_3I as a pure gas possesses a dielectric strength 1.2 times higher than SF_6, which makes it a suitable alternative to SF_6 in gas-insulated equipment [2]. The 100-yr GWP of CF_3I is 0.4, because the gas is rapidly decomposed by UV light when released into the atmosphere [3]. Previous experimental research has investigated CF_3I gas mixtures in terms of breakdown performances [4-5].

This paper investigates the breakdown characteristics of 30/70% CF_3I/CO_2 gas mixture in non-uniform field gaps for: (i) a lightning impulse waveform (1.2/50) and (ii) a steep-front impulse voltage waveform (rise time of 16 ns).

2 TEST EQUIPMENT SETUP

To carry out the investigation, two experimental setups were used to test a rod-plane electrode configuration: (a) a 400 kV Haefely impulse generator was used for the generation of a standard lightning impulse which leads to a gas discharge, (b) a steep-front impulse voltage generator that has a rise time of 16 ns was also used to investigate the V-t characteristic of the CF_3I gas mixture in the nanosecond range.

2.1 Lightning Impulse Generator

Fig. 1 shows the test setup at Cardiff University using the 400 kV standard lightning waveform. A capacitive voltage divider with a ratio of 27931 to 1 and 50 ns rise time was used to measure the lightning impulse voltage. A digital LeCroy wave-runner 64Xi was used to record the resulting waveform.

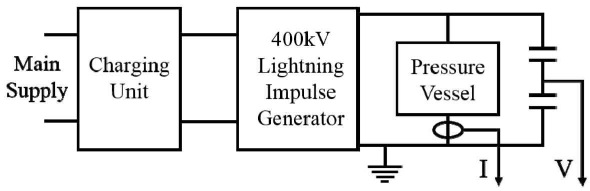
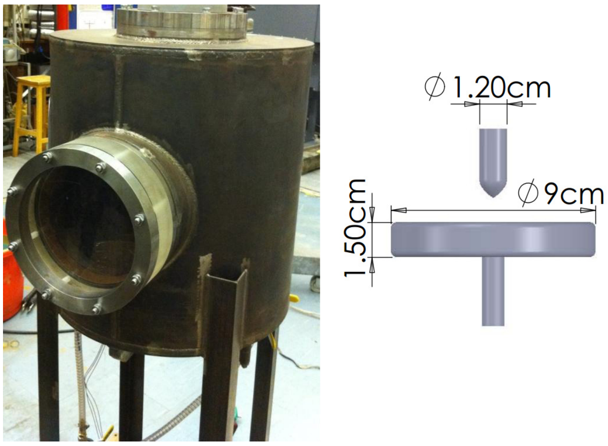


Figure 1: Test circuit for standard 1.2/50 lightning breakdown tests.

2.2 Developed Test Rig

To carry out the experiment, a pressure vessel made of mild steel was manufactured to withstand high gas pressure (Fig. 2a). The side window was made of polycarbonate, a tough thermoplastic material that has a high level of transparency. This enabled the viewing of gas discharge phenomena that occurred inside the vessel. At the bottom of the vessel, there are inlets and outlets for processes of pressurising and vacuuming the vessel [5]. A gas recovery system was also used in the experimental setup, so that CF_3I and its gas mixtures could be recycled. After each experiment, the tested gas mixtures were then transferred to their specified gas storage cylinders. In this test, a rod-plane electrode configuration as shown in Fig. 2b was chosen to represent a non-uniform electric field distribution.

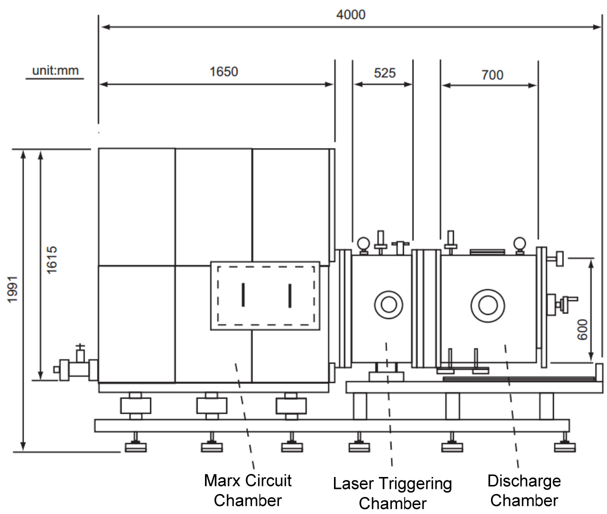


(a) *(b)*

Figure 2: a) Pressure vessel; b) Rod-plane electrode configuration.

2.3 Steep-Front Square Impulse Generator

Fig. 3 shows the schematic diagram of the steep-front square impulse voltage generator at Tokyo University. It consists of three main sections: a Marx circuit, a laser triggering system and a discharge chamber [6].



Rise time: 16 ns
Peak value: 40-200 kV
Duration: longer than 10 μs
Damping factor: less than 2.5% after 10 μs elapsed

Figure 3: Cross-sectional view of the generator [6].

During the operation, a fast impulse voltage was generated by the Marx circuit and the charge in the circuit was then transferred and stored in a capacitor. The spark gap was triggered by an Nd:YAG laser, which resulted in a steep-front square impulse voltage applied to the high-voltage electrode inside the discharge chamber. There is a Cobalt-60 radiation source installed on the back of the plane electrode to enhance the initial generation of electrons. This irradiation technique accelerate the electrons towards the anode and was used to overcome the statistical variability as reported in [7].

Two capacitive dividers were used to measure the voltage waveform: a high-frequency divider to measure the wave front and a low-frequency divider to measure the entire waveform. The voltage waveforms can then be recorded by a digital oscilloscope.

3 EXPERIMENTAL RESULTS

Breakdown tests were carried out on a 30/70% CF_3I/CO_2 gas mixture to determine the breakdown characteristics of the mixture in non-uniform field gaps. V-t characteristics were experimentally investigated under a standard lightning impulse waveform and the fast impulse of a steep front square waveform.

3.1 Experimental Methods

The experiments carried out for this paper follow the BS EN 60060-1 standards [8]. The multi-level method was applied for the steep-front square impulse experiment. First, several test voltage levels were chosen and subjected to 10 applied shots per voltage level. The percentage of breakdown at each level were counted and then plotted on a probability paper. From which, the 50% breakdown voltage (U_{50}) can be determined from a line of best fit when P(U) = 50%.

For the lightning impulse experiment, the up-down method was applied. The method requires the voltage to increase in steps of Δ U until a breakdown is recorded, then the voltage is reduced by ΔU. The process is repeated until a minimum of 30 impulse voltage applications were applied for every experiment. Based on the obtained data, the U_{50} can be determined using (1) or (2).

$$U_{50} = U_0 + \Delta U(\frac{A}{k} - 0.5) \qquad (1)$$

$$U_{50} = U_0 + \Delta U(\frac{A}{q} + 0.5) \qquad (2)$$

U_0 is the lowest breakdown voltage recorded in the series, k is the number of breakdown events and q is the number of non-breakdown events. The smaller of the two events will decide which equation to be used for calculating the U_{50}. Detailed explanation can be found in [9].

To minimise CF_3I gas costs, it was more cost-effective to carry out the up-down method for the lightning impulse experiment as it requires fewer number of shots. As both methods are recommended by the international standards, it is assumed that the difference in the obtained U_{50} would be negligible.

3.2 Breakdown Characteristics of Rod-Plane

The U_{50} was measured for the rod-plane configuration in terms of the effect of gap distance and pressure. The relationship between breakdown voltage and gap distance appears to be nonlinear as indicated in Fig. 4.

The rate of increase for breakdown voltage becomes more gradual when the gap spacing widens. The breakdown voltages measured for a 1 cm gap are comparable for lightning impulse and steep-front square voltage. However, for longer gaps, the breakdown voltage obtained from the steep front square waveform is considerably higher than its equivalent using lightning impulse. This may be explained by the significantly different rise times of the voltage generated by the two sources; for a steep-front square impulse, there is less time for the leader to propagate into the gap. Therefore, a much higher voltage was required for the leader to cross the gap and initiate a direct breakdown.

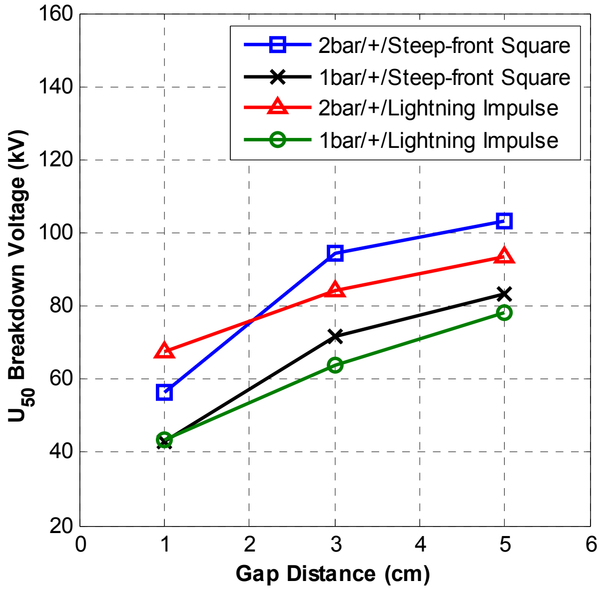


Figure 4: Comparison of breakdown voltages as function of gap distance for 30/70% CF_3I/CO_2 mixture.

3.3 V-t Characteristics of Rod-Plane

Non-uniform electric field distribution is achieved using a rod-plane configuration. V-t characteristics were investigated for gap distances of 1, 3 and 5 cm under gas pressures of 1 and 2 bar (abs.).

3.3.1 V-t for Lightning Impulse 1.2/50 Waveform

In Figs. 5 and 6, the breakdown voltage for the 1.2/50 waveform increases when the gap length and pressure increases. For 1 bar (abs.), most of the breakdown events occurred in less than 4 µs from the initial instant of the applied impulse. At 2 bar (abs.) and with higher gas density, there is more dispersion in the V-t results, with more breakdown instants after 4 µs. The majority of the instants of breakdown occurred in the wave tail region of the lightning impulse waveform (1.2/50). For a non-uniform field gap, there is a greater variation in the V-t results and normally the data will fall into a dispersion band. In a uniform or quasi-uniform field gap, the V-t characteristics show a more clearly defined trend.

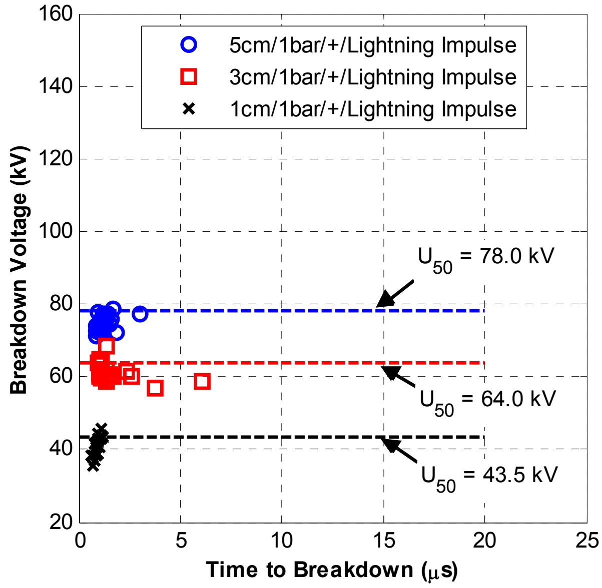


Figure 5: V-t characteristics of 30/70% CF_3I/CO_2 mixture for gap distances of 1, 3 and 5 cm under 1 bar (abs.) for positive lightning impulse (1.2/50).

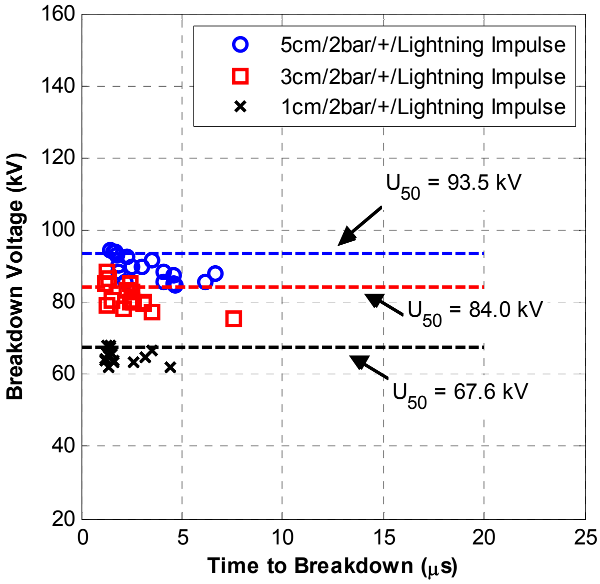


Figure 6: V-t characteristics of 30/70% CF_3I/CO_2 mixture for gap distances of 1, 3 and 5 cm under 2 bar (abs.) for positive lightning impulse (1.2/50).

3.3.2 V-t for Steep-Front Square Waveform

Figs. 7 and 8 show the V-t characteristics of the rod-plane configuration obtained from the steep-front voltage waveform. The experiment was carried out using pressures of 1 and 2 bar (abs.)

with a gap length of 1, 3 and 5 cm.

In general, with increasing gap distance and pressure, the breakdown voltages are higher. The majority of breakdown events occurred before 10 µs. However, the average breakdown time is shorter at higher pressures. From the V-t characteristics two main patterns can be observed: i) almost flat V-t curves and ii) V-t curves rising steeply in the short time region. In a non-uniform field gap, the time to breakdown is less sensitive to the increase in overvoltage. This may explain the steep rising curves in the short time region.

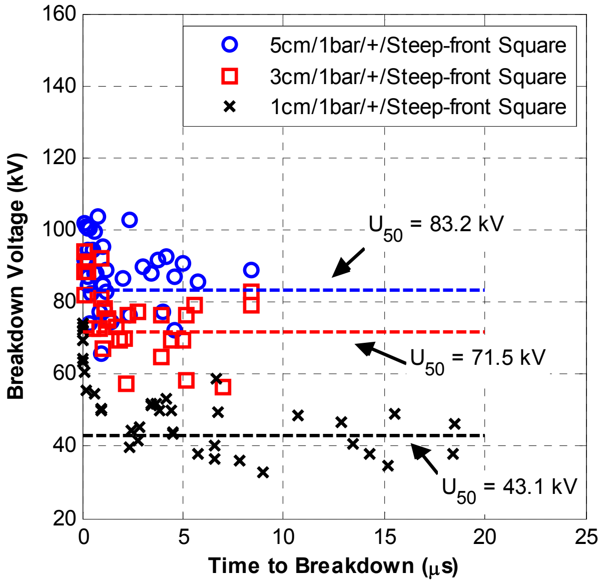


Figure 7: V-t characteristics of 30/70% CF_3I/CO_2 mixture for gap distances of 1, 3 and 5 cm under 1 bar (abs.) for steep-front square impulse voltage.

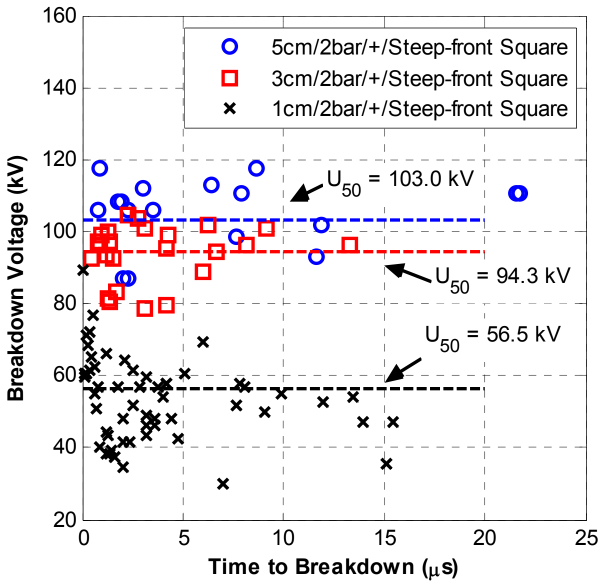


Figure 8: V-t characteristics of 30/70% CF_3I/CO_2 mixture for gap distances of 1, 3 and 5 cm under 2 bar (abs.) for steep-front square impulse voltage.

3.3.3 Comparison of V-t Characteristics

The comparison of V-t results obtained from the lightning impulse and steep front square waveforms are shown in Figs. 9 and 10. Overall, the results indicate less time-to-breakdown dispersion for V-t curves obtained by lightning impulse. However, the V-t results indicate longer average breakdown time for lightning impulse at higher pressure, whereas with steep-front square impulse, the average breakdown time is also shorter at higher pressure.

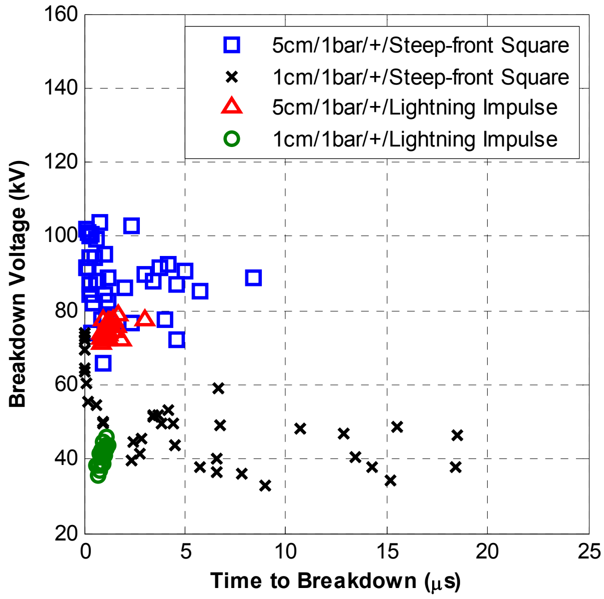


Figure 9: V-t characteristics comparison of 30/70% CF_3I/CO_2 mixture for gap distance of 1 and 5 cm under 1 bar (abs.) for both lightning impulse (1.2/50) and steep-front square impulse voltage.

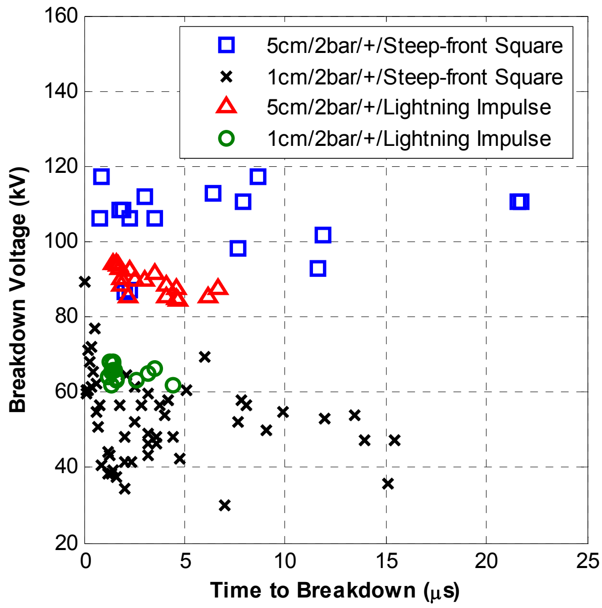


Figure 10: V-t characteristics comparison of 30/70% CF_3I/CO_2 mixture for gap distance of 1 and 5 cm under 2 bar (abs.) for both lightning impulse (1.2/50) and steep-front square impulse voltage.

4 BREAKDOWN CHARACTERISTICS IN GIS

Following the experiments carried out on the rod-plane configuration. Breakdown tests were carried out on a medium voltage (MV) gas-insulated switchgear (GIS) filled with a 30/70% CF_3I/CO_2 gas mixture to investigate the insulation capabilities of the proposed gas mixture.

4.1 Gas Insulated Switch Test Setup

A Ringmaster SF_6 switch disconnector was used to carry out the investigation. The rated AC voltage of the ringmaster is 13.8 kV and the rated lightning impulse withstand voltage is 95 kV.

The circuit diagram for the switch disconnector is shown in Fig. 11. Throughout the tests reported in this section, lightning impulses (1.2/50) were applied to one side of the switch disconnector using the Haefely impulse generator setup shown in Fig. 1. The switch disconnector was placed in the open position so that the 30/70% CF_3I/CO_2 gas mixture would insulate the open contacts. Lightning impulses were applied to one side of the open switch disconnector, one phase at a time. The remaining phases and all opposing contacts on the opposite side of the switch disconnector were earthed. A current transformer was placed around the earthing wire grounding the unit's opposing contacts to verify that a breakdown had occurred across the open switch disconnector. The switch disconnector was filled with 30/70% CF_3I/CO_2 at atmospheric pressure. This is the minimum operating pressure of the unit when filled with SF_6. All tests in this section were conducted in accordance with standards BS60060-1 [8] and BS62271-1 [10] for high voltage switchgear and controlgear.

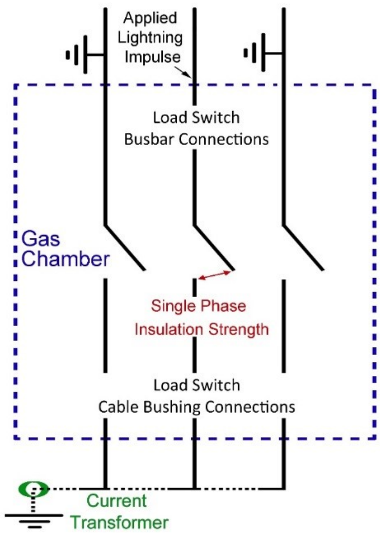


Figure 11: Lightning impulse test connections for MV Ringmaster switch disconnector.

The switch disconnector contacts resemble approximately the rod-plane contacts shown in Fig. 2b. However, as they are practical moving contacts that must be able to open and close quickly under a fault current, other considerations are taken into account in their manufacture that affect their shape. This means that such pratical contacts have a varying non-uniform electric field across their surface unlike the electrode system used previously. It is also important to note that the rod-plane configuration referred to in Sections 2 and 3 are fixed contacts with precisely controlled gaps whereas the contacts used in the switchgear have a nominal minimum seperation distance, the actual seperation distances of the contacts may vary and different from phase to phase. For this paper, it is resonable to approximate a contact seperation distance of 3 cm. The contacts were left unmodified and as manufactured. A contact design for a three phase switch [11] similar to the one used for testing in this paper is shown in Fig. 12.

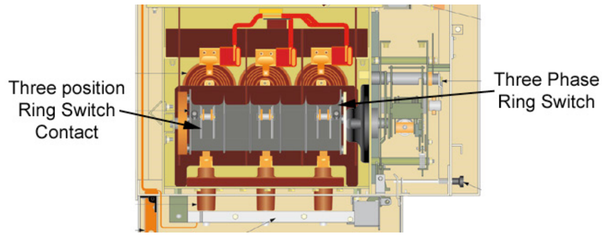


Figure 12: Three phase switch contact configuration similar to the contacts in the switch disconnector used in this paper [11].

4.2 V-t Characteristics in Gas Insulated Switches

Fig. 13 shows the V-t characteristics for 30/70% CF_3I/CO_2 in the gas insulated switch disconnector under positive lightning impulse at atmospheric pressure. It also shows a comparison of V-t results between GIS and rod-plane configuration for 3 cm gap distance.

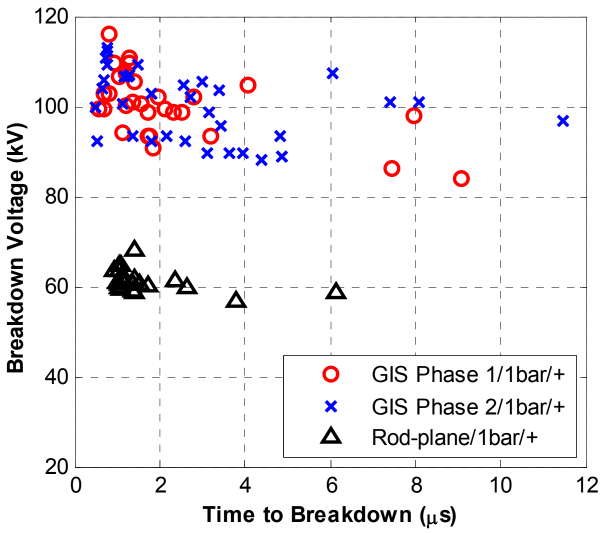


Figure 13: Comparison of V-t characteristics for 30/70% CF_3I/CO_2 mixture in GIS for a contact gap distance of 3 cm (approx.) and the 3 cm rod-plane configuration. Both experiments were carried out under 1 bar (abs.) and positive polarity.

As can be seen on the figure, good correlation is obtained between the results for two different sets of contacts in Phases 1 and 2. It can be observed that under a positive lightning impulse, 89% of the gas mixture breakdowns occurred within 5 μs after the impulse was initiated as with previous tests. The results also show that under positive lightning impulse, 62% of breakdowns occurred less than 2.5 μs after the impulse was initiated. The higher breakdown voltage in the switchgear case is attributed to the fact that the electric field between the contacts is more uniform than between the rod-plane electrodes.

5 CONCLUSION

The breakdown performance of a 30/70 ratio CF_3I/CO_2 gas mixture was investigated for a rod-plane electrode configuration and across contacts of a practical GIS switchgear unit. The obtained V-t characteristics were analysed, and the results show that, for the lightning impulse, there is less breakdown time dispersion. At 2 bar (abs.), the characteristics indicate longer average breakdown time for lightning impulse in comparison to the steep-front square impulse. The results show that the V-t characteristic of a 30/70% CF_3I/CO_2 gas mixture changes depending on the gap spacing and the gas pressure. The measured breakdown results obtained at longer gap distance for steep-front square impulse are comparatively higher than the lightning impulse equivalents. This may have been caused by the significant difference in rise times of the voltage generated by the two sources. Further tests are proposed for the same gas mixture using practical circuit breaker contact electrode configurations that represent more uniform field distribution.

ACKNOWLEDGMENTS

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