Evaluation on current interruption ability of CO2 and SF6 using current and voltage application highly controlled by power semiconductors

Evaluation on Current Interruption Ability of CO_2 and SF_6 using Current and Voltage Application Highly Controlled by Power Semiconductors.

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Abstract— This paper reports a new simple test technique to evaluate current interruption ability of arc quenching gases. In the test, current and voltage applied to the arc was controlled using a insulated gate bipolar transistor (IGBT). Switching the IGBT enables us to produce free recovery conditions for a fundamental arc decay in nozzles. In addition to this, a voltage was intentionally applied to the free recovery arcs between the electrodes by switching-off IGBT again at the specified delay time t_{d}. This applied voltage is called quasi transient recovery voltage (quasi-TRV). We can evaluate successful interruption or interruption failure by measuring the current between the electrodes after quasi-TRV application. We compared the interruption ability of SF_6 and CO_2 through this developed technique. The experimental results show that a residual arc in SF_6 gas flow decays four times more rapidly than that in CO_2 gas flow. Influence of observation holes in the nozzles used in the experiments was also investigated, showing less influence of observation on the arc behavior.

Index Terms— Circuit breaker, SF_6, IGBT, CO_2, Current interruption

I. Introduction

SF_6 is widely used as an arc quenching medium for gas circuit breakers (GCB) from its high current interruption abilities. However, the global warming potential (GWP) of SF_6 is 22800 times higher than that of CO_2. Therefore, alternative gases for SF_6 is strongly desired not only gas insulation but also arc quenching medium. In order to take the place of SF_6 by the alternatives, detailed understanding of the residual arc properties in current interruption process is essential.

The authors have been investigating on the quenching process of gas-blast arcs fundamentally from both numerical and experimental approaches. For the experiment, we use a DC current source and a power semiconductor, insulated gate bi-polar transistor (IGBT) to control current and voltage for the arc plasmas with an accuracy in time. Previously, the arc behavior and electron density in the arcs in the gas flow were measured in detail by using a laser Thomson scattering (LTS) under free recovery condition of the arcs [1], [2]. In addition to these, the arc behavior has been observed using a high speed video camera for visible light from the arc. From these experimental results, we found a steeper drop in the electron density in the residual arc in gas flow if the gas has higher interruption ability. In addition, radiation intensity of the arc can be also attenuated more rapidly by the gas with a high interruption ability.

In this paper, we again applied a new simple method for evaluation on the current interruption ability of arc quenching gases [3]. The method is as follows: the free recovery condition of the arc was made to create decaying arcs. At certain delay time t_{d} after the arc started decaying, a voltage is applied to the decaying arcs. This applied voltage is called quasi transient recovery voltage (quasi-TRV). If dielectric recovery between the electrodes is enough, the arc continues to decay and then the successful interruption is obtained. If the arc re-ignites between the electrode, we have interruption failure. The residual arcs in SF_6 and CO_2 gas flow were tested in this work. The current interruption ability of each gas was defined with which 50% of successful interruption is obtained by the t_{d} . As results, SF_6 gas flow decayed the arcs in 30 μs, while CO_2 gas flow requires 120 μs for successful interruption. Using the developed method, we can obtain the systematic data about interruption rate for various gases on the high accuracy controlled time domain.

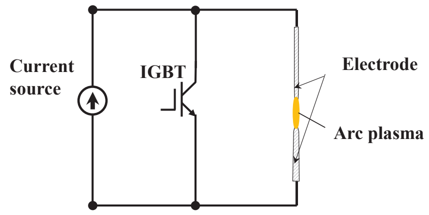


Fig. 1. Conceptual circuit for investigation of decaying arcs and arc re-ignition.

II. Application of quasi-transient recovery voltage to gas-blast arcs under free recovery condition

The main purpose of the present work is to investigate the recovery property of gas-blast arcs under free recovery condition. In order to obtain the recovery property, we need to apply recovery voltage to the residual arc. Use of IGBTs, which are power semiconductors, enables us to generate free recovery condition for arcs and then to apply recovery voltage between the electrodes with time accuracy. Fig. 1 illustrates the conceptual circuit for the present test. The arc plasma is ignited between the electrodes powered by a current source. In parallel with the electrodes, an IGBT is connected. Switching the IGBT 'ON' generates the arc under free recovery condition. In this state, we can study the arc decaying process fundamentally. At a specified delay time t_d after the arc decaying starts, switching the IGBT 'OFF' can apply recovery voltage between the electrodes from the current source. This recovery voltage is here called 'quasi-TRV' because it is not a regular TRV but is similar to it. We can change t_d in micro-seconds with a high accuracy in time.

Figs. 2 and 3 indicate the conceptual diagram of the currents and voltages in cases of successful interruption and interruption failure, respectively. The successful interruption is defined when the arc current continues to decrease even after quasi-TRV application. On the other hands, when the arc current increases with quasi-TRV application, it is defined as the interruption failure. This method with tens of test shots can easily determine the interruption probability for different t_d, for different gas conditions such as gas species and gas flow rates. This interruption probability test thus offers systematic and fundamental data for current interruption.

III. Experimental setup, experimental procedure and experimental condition

A. Gas-blast arc device

Fig. 4 shows the experimental setup for gas-blast arcs and the electric circuit used in the experiment. The setup includes a current source, the arc device, and an IGBT parallel connected with the electrode. The arc device has a fixed electrode, a movable electrode and a nozzle. The gap length between the electrodes is 50 mm in open state. Various gases can be blown to the arc from the bottom of the system.

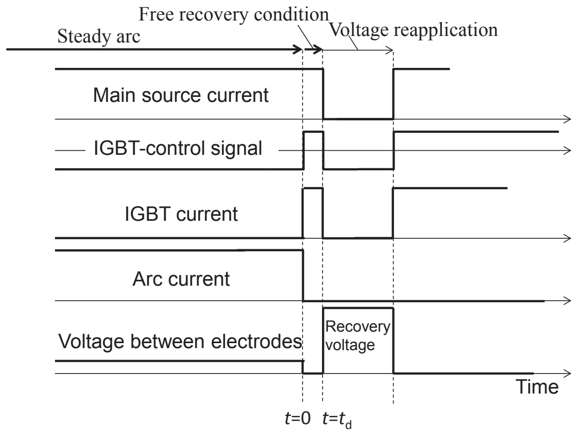


Fig. 2. Conceptual current and voltage behaviors in case of success of arc interruption after quasi transient recovery voltage application.

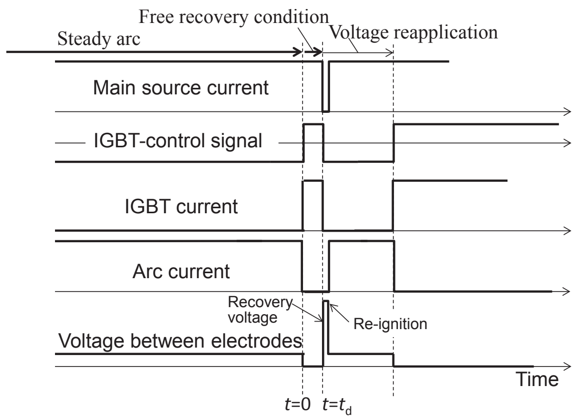


Fig. 3. Conceptual current and voltage behaviors in case of interruption failure after quasi transient recovery voltage application.

Fig. 5 shows the gas-blast nozzle that we used in the experiment. The nozzle is made of PTFE and its shape is cylindrical. The height of the nozzle is 130 mm and the internal diameter varies from 10 mm to 40 mm corresponding to the axial position. The inner diameter of the nozzle on the bottom side is 40 mm, and the inner diameter of the nozzle on the top side is 18.75 mm. The nozzle has a throat with a length of 10 mm and a diameter of 10 mm. The nozzle-throat, which has the smallest diameter, plays an important role for the arc shrinkage. The nozzle has observation holes for laser Thomson scattering near the nozzle-throat. The observation holes are made perpendicular to the nozzle axis. In the present experiments, the observation holes were covered by BK7 glass plates to avoid the gas flow out through the holes.

B. Experimental condition and procedure

Experimental procedure is as follows. Fig. 6 presents the current-voltage waveforms in whole time scale in the experiment. The waveform of 'Source CT' is the output current from the current source. The voltage waveform with a term 'Cylinder voltage' is the AC driving voltage provided to a air-cylinder

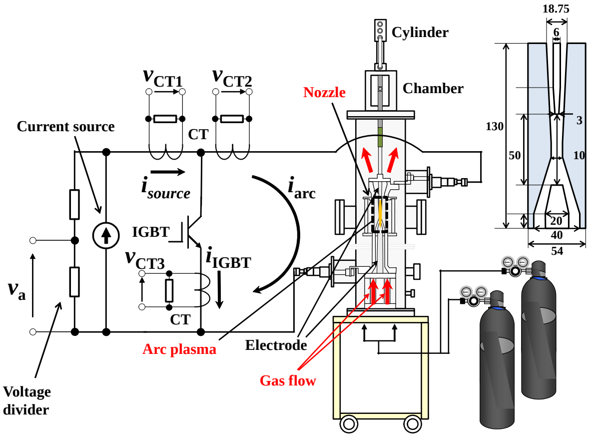


Fig. 4. Experimental setup for gas-blast arc experiment.

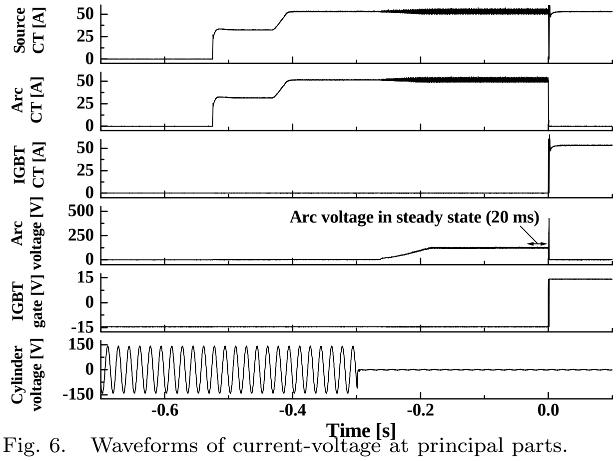


Fig. 6. Waveforms of current-voltage at principal parts.

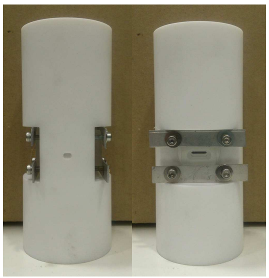


Fig. 5. Gas-blast nozzles for the experiments

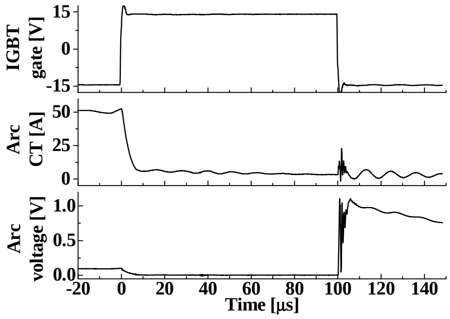
to move the electrode. With application of AC 100 V input, the electrode is supposed to be closed. If the voltage supply is stopped, the electrode will start opening. At the initial state, the electrode is closed and the IGBT is switched OFF. As the first step of the experiment, we vacuum the arcing chamber using vacuum pumps. The next, the object gas is injected into the vacuumed chamber at the flow rate of 100 L/min from the bottom of the chamber. The estimated velocity at the gas inlet is about 1.8 m/s. This gas injection raises the pressure in the chamber. At the time the chamber pressure reaches to 1 atm, the current source starts feeding with DC 30 A current. The current gradually increased to DC 50 A, which is the objective value for the experiment. At 100 ms after source current reached 50 A, the voltage to the cylinder is set to zero, the electrode starts opening with a little delay. Concurrently with the electrode opening, the arc ignites between the electrodes. While the electrode stroke, the voltage between the electrode rises up to the arc voltage in steady state. The steady state is kept for about 200 ms. At a certain timing 0.0 s, 'ON' signal is inputted to the IGBT gate.

Fig. 7 shows enlarged waveforms of IGBT signal, the arc current and the arc voltage around the time t = 0.0 s. The turning 'ON' IGBT transfers the current from the arc to the IGBT. The arc current goes to zero in some tens of micro seconds, as well as the arc voltage goes to zero. From $t = 0.0$ s, the IGBT signal is kept 'ON' for the specified time 10 – 500 μs. This 'ON' time for IGBT is defined as a delay time $t_{\rm d}$ because the turning-off IGBT applys the voltage again between the electrodes at $t_{\rm d}$ from $t = 0.0$ s. The voltage applied to free-recovery arcs is similar to transient recovery voltage (TRV) so we call it 'quasi-TRV'. The peak voltage of quasi-TRV is about 1 kV and the rate of rise of the voltage (RRRV) is nearly 2 kV/μs. Using application of quasi-TRV, we can evaluate the arc interruption ability of the system. If dielectric recovery between the electrode is enough, current will not flow through the electrode and the arcing space (successful interruption), otherwise the arc re-ignites between the electrode (interruption failure). Therefore long $t_{\rm d}$ leads to successful interruption. Nevertheless, there is a probability distribution with interruption results. We hence evaluate the arc interruption abilities of gases from $t_{\rm d}$ with which the interruption probability is 50%.

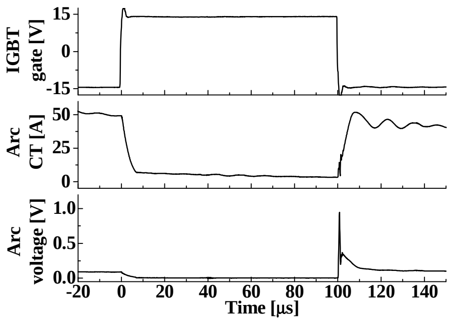
In this work, we performed the evaluation on the arc interruption abilities of the object gases using the PTFE nozzles. The successful interruption probability and the steady state arc voltage were determined for the evaluation.

IV. Evaluation results on arc interruption ability of SF_6 and CO_2.

Fig. 8 shows the probability of successful interruption for SF_6 blast and CO_2 blast arcs using the nozzle with covered holes as shown in Fig. 5. This figure indicates that the increasing delay time $t_{\rm d}$ elevates the successful interruption probability up to 100%. For example, as seen in Fig. 8, when the delay time $t_{\rm d}$ was set to 20 μs, eight to thirty-seven tests brought successful extinction of SF_6 gas blast arcs. On the other hand, the delay time of $t_{\rm d} = 25$ μs provides five successful interruptions in nineteen interruption tests. The successful interruption probability increases to seven-to-ten tests at $t_{\rm d} = 30$ μs for SF_6 gas blast arcs. In addition, we can see that the successful probability depends markedly on the gas kind. For example, one-eleventh of CO_2 blast arc tests were interrupted



(a) successful interruption



(b) Interruption failure

Fig. 7. Enlarged waveforms of current-voltage around the time 0.0 s.

in cases of t_d of 90 μs. The successful interruption probability of CO_2 gas blast arcs increases to three-sixteenth for $t_d = 100$ μs. By comparing two lines of interruption probability for SF_6 and CO_2, there seems more strong dependence on t_d for SF_6 than CO_2. This implies that SF_6 arcs decay much rapidly with time.

From Fig. 8, we estimated t_d for 50% of interruption probability for each of gases. Fig. 9 indicates the estimated t_d for 50% of the interruption probability. SF_6 gas flow provides $t_d = 28$ μs to have 50% interruption probability. On the other hands, CO_2 requires $t_d \geq = 130$ μs to have more than 50% of interruption probability. This means that the arc interruption ability of SF_6 is 4.6 times higher than that of CO_2. This result demonstrates that our simple method can evaluate the arc interruption ability, and it can be adopted to compare the interruption ability of different gases under the same conditions.

The arc voltage is one indicator for arc resistance under a DC current. In this work, the arc voltage in steady state is defined as the averaged arc voltage measured in the 20 ms before the arc current down by switching on the IGBT as shown in Fig. 6. Fig. 10 shows the averaged arc voltage in steady state for SF_6 and CO_2 gas blast arcs. The averaged arc voltage was calculated from at least 30 shots under the same conditions. As indicated here, SF_6 gas blast arc has the averaged arc voltage of about 195 V, while the averaged arc voltage of CO_2 is about 141 V.

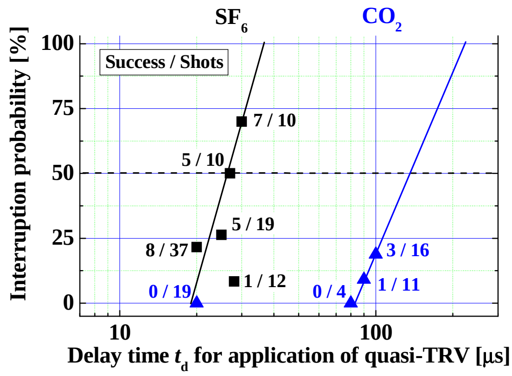


Fig. 8. Dependence of successful interruption probability on delay time t_d for quasi-TRV application, in cases of the nozzle with holes covered by plates.

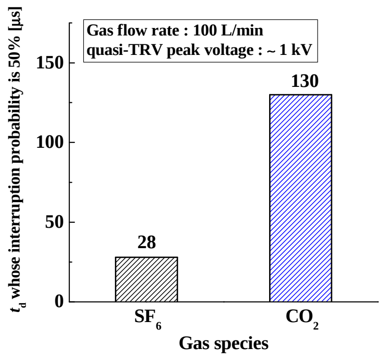


Fig. 9. Estimated t_d for 50% of interruption probability.

V. The influence of the observation holes for a laser path in the nozzle on the arc interruption ability of the blast gas

The experimental results above were obtained using the nozzle with observation holes covered by glass plates, as showed in Fig. 5. The observation holes of the nozzle were installed for a laser Thomson scattering measurement. The observation holes was covered by glass plates to reduce the influence of holes in the nozzle. In this section, we checked the influence of the existence of the observation holes for a laser path on the arc interruption ability of the blast gas using the nozzle with holes covered by glass plates or

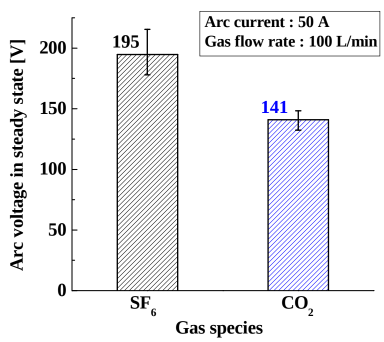


Fig. 10. Averaged arc voltage measured in steady state.

Fig. 11. The nozzle with uncovered holes.

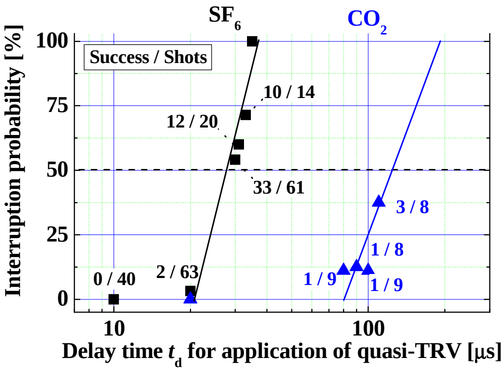


Fig. 12. Dependence of percentages of successful interruption on delay time t_d for quasi-TRV application, in the cases of the nozzle with uncovered holes.

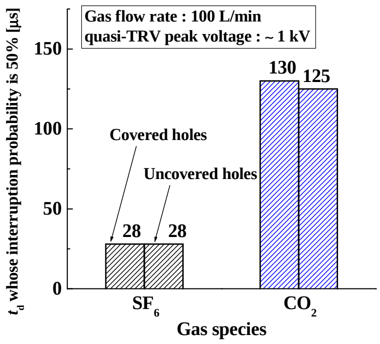


Fig. 13. Estimated t_d whose interruption probability is 50%.

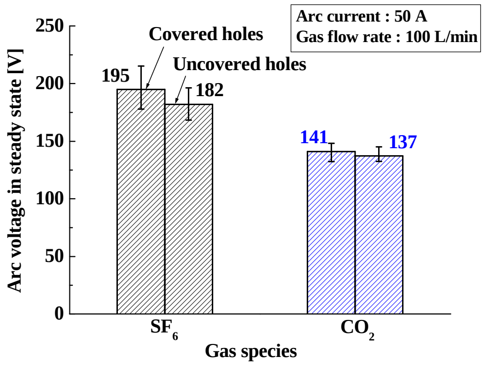


Fig. 14. Averaged arc voltage measured in steady state.

uncovered as shown in Fig. 11.

Fig. 12 indicates the interruption probability versus delay time t_d for quasi-TRV application in cases of the nozzle with uncovered holes. Compared between Fig. 8 and Fig. 12, there is little difference in interruption probability, taking into account the comparison between the case of nozzle with covered holes (Fig. 5) and that with uncovered holes (Fig. 11). . SF_6 gas flow provides the interruption probability varying sharply around $t_\mathrm{d} = 30\ \mu$s, while CO_2 gas flow offers t_d ~80–200 μs for interruption probability from 0 to 100%. Fig. 13 illustrates the comparison of t_d for 50% interruption probability in cases of the nozzle with holes covered or uncovered by glass plates. For each of gases, the left bar indicates the result for the nozzle with covered observation holes, and the right bar shows the result for the nozzle with uncovered holes. As seen, there is little difference between the results of holes covered or uncovered by glass plates. Fig. 14 represents the averaged arc voltage measured in their steady states for each of nozzles with holes covered or uncovered by plates. As for the averaged arc voltage, there is not a big influence between them. Thus, we can say that for CO_2 and SF_6 arcs, the existence of holes in the nozzle causes little electrical influence on the arc plasma.

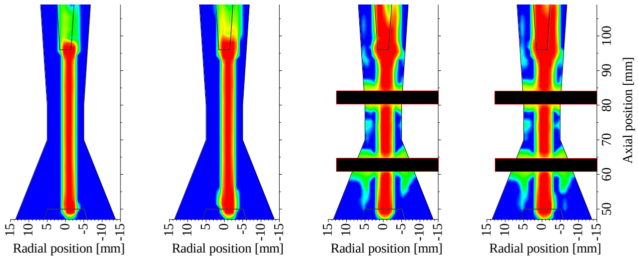
VI. High speed video camera observation on SF_6 and air arcs

This section describes a result of high speed video camera observation to understand the arc behavior in the nozzle. For this purpose, polymethylmethacrylate (PMMA) nozzles transparent for visible light were used. In these experiments, we also checked the influence of the observation holes in the nozzle on the arc behavior. Fig. 15 shows the nozzles used for high-speed video camera observation. The difference between the nozzles (a) and (b) is that the nozzle (b) has observation holes. The nozzle (b) is identically shaped with the nozzle with covered holes shown in Fig. 5. In the experiments, the observation holes were covered by BK7 glass plates to avoid the gas flow out through the holes. If the observation holes is covered effectively, the shape of arc sustained in the nozzle with holes covered by plates will be identical to that in nozzle without holes. For the high speed video camera observation, SF_6 and air arcs were selected.

Fig. 16 shows the images of visible light emission from the air blast arcs in the nozzle. The images are colored artificially depending on the radiation intensity. Fig. 16 (a) depicts the arc shape sustained in the normal nozzle (Fig. 15(a)) captured at the time of $t = -50$ ms. At the time -50 ms, the electrode is fully opened and the arc current was 50 A. The panel (b) presents the image of the air blast arc with an arc current of 50 A at the another timing. As indicated in these figures, the arc shape hardly changed in 50 ms between panels (a) and (b). It is also confirmed that an air arc tends to be straight and morphologically stable. Fig. 16 (c) and (d) depict the images of the air blast arc sustained in the nozzle with holes covered by

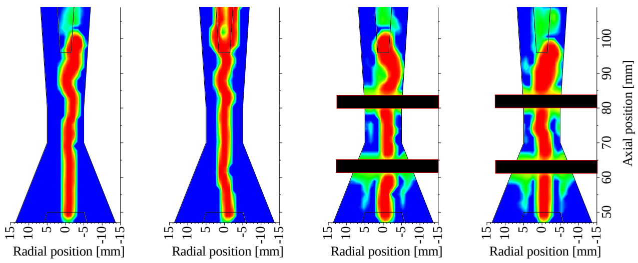
(a) Normal (b) Covered holes

Fig. 15. Gas-blast nozzles for the high speed video camera observation.



(a) -50 ms (b) 0ms (c) -50 ms (d) 0ms

Fig. 16. The visible light emission from air blast arc sustained in the nozzle. (a) without holes at $t = -50$ ms and (b) without holes at $t = 0$ ms. (c) with holes covered by plates at $t = -50$ ms and (d) with holes covered by plates at $t = 0$ ms.



(a) -50 ms (b) 0ms (c) -50 ms (d) 0ms

Fig. 17. The visible light emission from SF_6 blast arc sustained in the nozzle. (a) without holes at $t = -50$ ms and (b) without holes at $t = 0$ ms. (c) with holes covered by plates at $t = -50$ ms and (d) with holes covered by plates at $t = 0$ ms.

plates (Fig. 15(b)). These were captured at the timing of $t = -50$ ms and 0 ms, respectively. In Fig. 16, the metal plate to fix the glass are indicated by black bars. As seen in these figures, there is l little difference in the visible light emission from arcs in panel (a) and (c). This implies that the observation holes hardly affects the behavior of air blast arcs.

Fig. 17 shows the visible light emission from the SF_6 blast arcs. The panels (a) and (b) shows the arc sustained in the normal nozzle (Fig. 15(a)) captured at $t = -50$ ms and $t = 0$ ms, respectively. The panels (c) and (d) indicates the arc image in the nozzle with holes (Fig. 15(b)) observed at $t = -50$ ms and $t = 0$ ms, respectively. Between panels (a) and (b), the shape of the SF_6 blast arc changed considerably in 50 ms. This result shows that a SF_6 blast arc is markedly affected by gas flow especially with turbulent effects. Comparison between panels (a) and (c) indicates that the arc shape is similar in panel (a) to that in panel (c). From the results, we judged that there is little influence of the observation holes on the arc behaviors in the nozzle.

VII. Summary

In this paper, a new simple test technique has been proposed to evaluate current interruption ability of arc quenching gases. This test technique controls the current and voltage applied to the arc with time accuracy using a insulated gate bipolar transistor (IGBT). By switching the IGBT parallel connected with the arc electrodes, free recovery conditions can be obtained for a fundamental arc decay in the nozzles. Furthermore, a quasi transient recovery voltage (quasi-TRV) was applied between the electrodes after initiation of the free recovery condition. The quasi-TRV is applied at the specified delay time t_{d}. From this method, the interruption probability were measured for different t_{d}. The interruption ability of SF_6 and CO_2 were compared using this developed technique. The experimental results show that a residual arc in SF_6 gas flow decays four times more rapidly than that in CO_2 gas flow. Influence of observation holes in the nozzles used in the experiments was also investigated, showing less influence of observation on the arc behavior.

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