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THERMAL CURRENT INTERRUPTION PERFORMANCE OF CO_2 AND CO_2/C_4F_7N MIXTURE

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Abstract. This contribution aims to compare the thermal interruption performance of pure CO_2 with a mixture of CO_2/C_4F_7N. Measurements primarily show higher interrupting capability for a mixture with C_4F_7N. Detailed analysis shows a distinct difference in the failure mechanism which for CO_2/C_4F_7N is thermal failure and for CO_2 mostly "hot dielectric" failure. The difference in the failure mechanism is relevant for the test duties with the most severe TRV. The influence of ablated nozzle material on the interruption process can be ruled out.

Keywords: SF6 Alternatives, Switching, Electric Arc, GIS, Circuit Breakers.

1. Introduction

In recent years, changes in environmental policies have motivated the development of SF_6-free gas insulated switchgear. In high voltage gas circuit breakers (CB), instead of SF_6, which was widely used for decades, gas mixtures with CO_2 as the base are considered as replacements. The most common additives to the base gas today are O_2 and the fluorinated gases C_4F_7N or $C_5F_{10}O$. Many publications have reported CB performance using SF_6 alternatives [1, 2], often with comparisons to the performance using SF_6 [3–8]. These studies typically used commercial CBs, designed and optimized for one gas, usually SF_6.

In the High Voltage Laboratory of ETH Zurich, an experimental setup based on a puffer-type CB has been developed. This setup was not optimized for any gas, and allows for the adaption of parameters to keep conditions (upstream pressure, arc length) at current zero (CZ) identical for each gas. This experiment has been used together with a synthetic test circuit to investigate the influence to thermal current interruption performance that results from adding C_4F_7N into CO_2. Also, the influence of the nozzle material (PMMA and PTFE), was investigated.

2. Methods

The measurements were performed with a test device based on the puffer circuit breaker principle (henceforth puffer CB), shown in Figure 1, stressed by a synthetic test circuit [9]. During all measurements, trigger timings of the experiment were set to allow for the same arc length, (43 ± 1) mm, and blow pressure, $\Delta p = (5.85 \pm 0.1)$ bar, at the CZ instant. Arc length was measured with a linear potentiometer, and blow pressure with two transient pressure sensors installed in the puffer cylinder. The puffer CB vessel was always filled with 5 bar absolute of gas. The experimental vessel volume was large, approximately 750 l, to allow for a high number of arcing events without the risk of too high decomposition of the gas. The gases investigated were pure CO_2 and a mixture of CO_2/C_4F_7N with 5% concentration of the fluorinated additive. Mixing of the gas was performed in the experimental vessel as described in [10]. For CO_2, two nozzle materials were used, PMMA (Polymethyl methacrylate) and PTFE (Polytetrafluoroethylene) filled with MoS_2, both with the same geometry. PTFE is a standard nozzle material used in CBs, and PMMA was used to allow for optical access to the arc [11]. The goal of making measurements with both materials was to confirm that there is no influence of the nozzle material on the thermal interruption performance in this experimental puffer breaker. The nozzle throat diameter was chosen to achieve the maximum pressure build-up and still guarantee sonic flow conditions for optimal arc cooling while at the same time minimizing nozzle ablation and backheating. To minimize erosion of arcing contacts and nozzle and to exclude backheating, the current of the high current part of the synthetic circuit was limited to a peak of about 2 kA.

To determine the thermal limit of each gas, a series of measurements were performed spanning a range of prospective $\mathrm{d}i/\mathrm{d}t$ settings, with a step size of approximately 0.33 A/µs. For each $\mathrm{d}i/\mathrm{d}t$ setting at least 5 repetitions were made, with up to 3 additional measurements for $\mathrm{d}i/\mathrm{d}t$s around the threshold. This procedure was maintained until only failures were observed for the highest $\mathrm{d}i/\mathrm{d}t$ and only successes for the lowest $\mathrm{d}i/\mathrm{d}t$. The TRV after current zero adhered to a 450 Ω surge impedance, with the peak after approximately 13 µs. This voltage stress is similar to the short line fault (SLF) 90 test duty for a 245 kV circuit breaker.

The results were analyzed according to the method proposed by Engelbrecht *et al.* [12]. In this method, the probability p of success for each prospective $\mathrm{d}i/\mathrm{d}t$ setting is determined from a binominal distribution treatment. Consequently, a Gaussian cumulative distribution function may be fit to the probabilities of success for each $\mathrm{d}i/\mathrm{d}t$-range to determine the inter-

Figure 1. Experimental setup of Puffer CB

ruption limit at $p = 0.5$. An example of such a fit performed for CO_2/C_4F_7N is shown in Figure 2.

3. Results & Discussion

3.1. Thermal Limit and Extinction Peak of CO_2/C_4F_7N mixture

Results from measurements with the CO_2/C_4F_7N gas mixture are shown in Figure 2. The thermal interruption threshold was calculated to be (8.97 ± 0.26) A/µs with 2σ uncertainty interval.

Another parameter often considered as an indicator of thermal interruption performance is the arc extinction peak [13]. Extinction peak values measured for all experiment repetitions in CO_2/C_4F_7N are shown in Figure 3. Based on those results, the threshold value for successful interruption seems to be in the range from 1.2 kV to 1.3 kV, with the exception of one fail at almost 1.7 kV. Given values are compensated for induced voltage from parasitic inductance.

The obtained thermal interruption limit is identical, within the uncertainty, to the limit found by Radisavljevic *et al.* [2] for a mixture of $CO_2/O_2/C_4F_7N$ (80/10/10), with unreported blow pressure. Lee *et al.* [3] used the same gas mixture as the present experiment with a higher filling pressure, 8 bar, in SLF 90 test duty. They reported successful interruption at 9.6 A/µs and failure at 10.7 A/µs, but also at unreported blow pressure. In our experiment the highest successful interruption was observed in the same range of di/dt, at 9.5 A/µs.

The limit of 9 A/µs suggests that the breaker with CO_2/C_4F_7N gas mixture and the selected parameters, could with 50 % probability thermally interrupt a 50 Hz short circuit current of 22.5 kA in SLF 90 switching duties.

3.2. Comparison of pure CO_2 and CO_2/C_4F_7N mixture

A comparison of the interruption performance for both pure CO_2 and CO_2/C_4F_7N mixture is shown in Figure 4. Those results show an increase of the

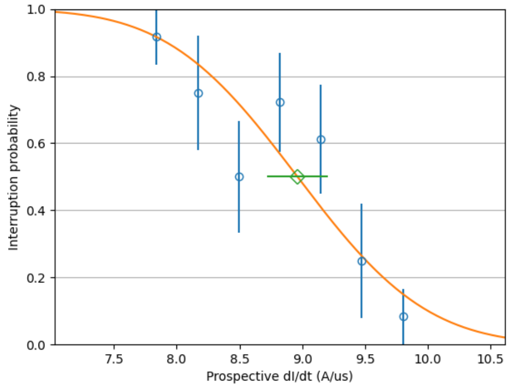

Figure 2. Thermal interruption limit determination of CO_2/C_4F_7N. Blue circles and lines - the probability of success from the binomial distribution, orange line – cumulative function fit, green diamond – interruption limit with two sigma uncertainty interval.

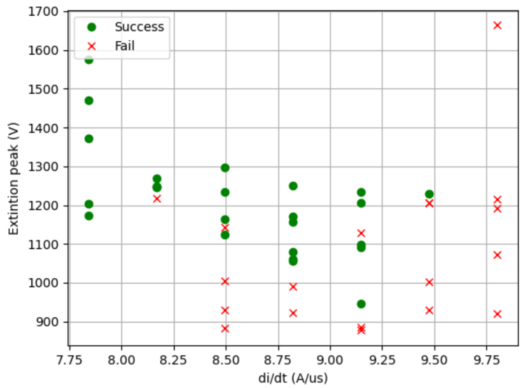

Figure 3. Extinction peak in function of di/dt measured in CO_2/C_4F_7N gas mixture.

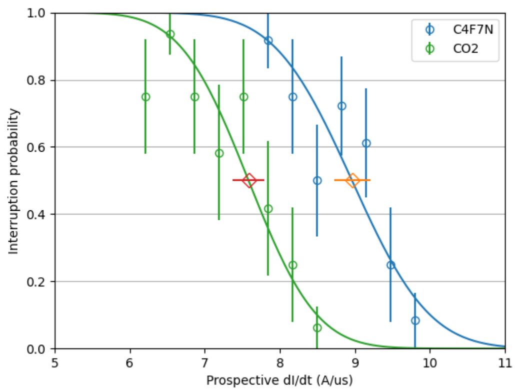

Figure 4. Thermal interruption limit for CO_2 and CO_2/C_4F_7N

interruption threshold from (7.59 ± 0.22) A/µs for pure CO_2 to (8.97 ± 0.26) A/µs in mixture with C_4F_7N.

The increase of almost 20 % was unexpected, as the literature claims no improvement of the thermal interruption performance brought by C_4F_7N to CO_2 [2, 5]. The blow pressure and arc length for both gases were identical to within the tolerance range and should not influence the results. Despite all experimental condi-

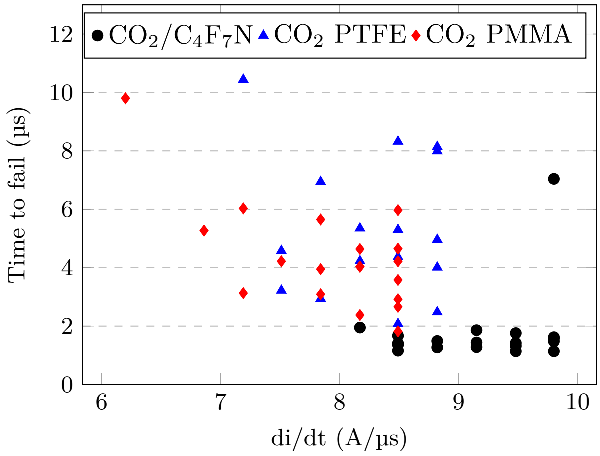

Figure 5. Time to fail

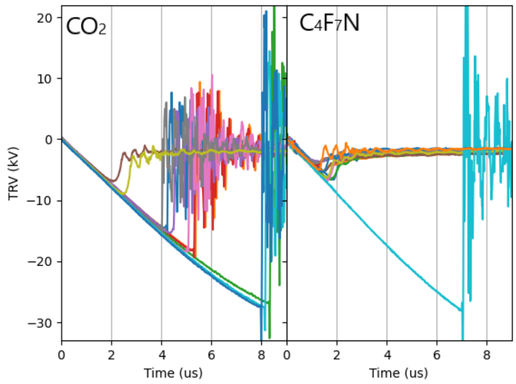

Figure 6. Few TRV measurements in case of failures in CO_2 left and in CO_2/C_4F_7N right

tions being kept constant, we do observe a significant difference in the time to fail (TTF) which is shown in Figure 5. It has been calculated for all failures based on the time instants of voltage zero-crossing and the peak of the transient recovery voltage (TRV) after which the voltage collapsed due to the re-ignition of the arc. TTF in the mixture of CO_2/C_4F_7N was less than 2 µs for all cases except one. TTF in CO_2 was significantly higher, and most of the cases were in the range from 4 µs to 10 µs. Looking into the voltage waveform, shown in Figure 6, it is visible that for earlier failures the voltage collapse has a much smaller du/dt, in contrast to later failures, from around 4 µs to 5 µs, where du/dt is higher and there is a sharp transition.

This could mean that late failures in CO_2 are not thermal failures, caused by thermal runaway from the post arc current, but rather "hot dielectric" failures. Adding C_4F_7N to CO_2 reduces the probability of such "hot dielectric" failures, as the fluorinated additive improves the insulation properties of the mixture. In this case, the presented values for the thermal interruption limit of CO_2 are underestimated, as they treat "hot dielectric" breakdowns as failures, although the thermal phase was cleared. Figure 7 shows a plot with a binomial probability distribution for CO_2

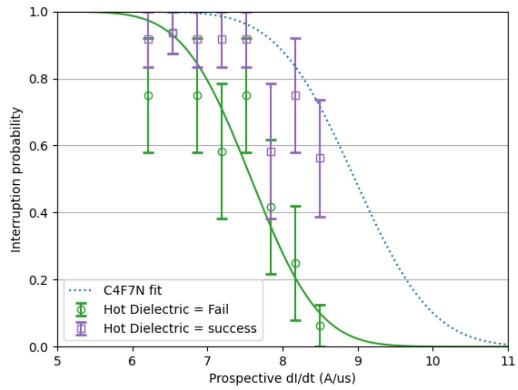

Figure 7. Influence of "hot dielectric" breakdowns treated as failures (green) or successes (purple) to determine thermal interruption performance of CO_2. The fit of CO_2/C_4F_7N is plotted as reference.

results with considering the late and steep "hot dielectric" breakdowns as a successful thermal interruption. Those results show that the real value for the thermal interruption threshold could be expected in higher regions of di/dt, roughly in the same range as for CO_2/C_4F_7N.

For a mixture of CO_2/C_4F_7N only one "hot dielectric" failure occurred. Treating it as a thermal success does not change the thermal limit according to the uncertainty given in the previous section. For the extinction peak plot shown in Figure 3, this one "hot dielectric" failure corresponds to the outlying point with the highest voltage at extinction for the highest di/dt setting. Excluding this failure makes the extinction peak threshold value near 1.2 kV more clear.

To determine the real value of the thermal interruption limit of CO_2, more measurements need to be performed with higher di/dt, and analysis has to focus on separating the failures with low du/dt voltage collapse after the peak of the TRV. Post arc current (PAC) measurements could be used to verify if the fail was thermal, i.e. it occurs during PAC, or "hot dielectric", occurring after PAC.

The "hot dielectric" mechanism of failure gives the CO_2/C_4F_7N gas mixture higher performance than pure CO_2 when considering switching duties where the first line peak does not occur within the first few µs after CZ, like some SLF duties. It should also be noted that the experimental puffer CB design and the selected contact separation distance at CZ are not optimized for electric withstand.

3.3. Comparison PMMA and PTFE nozzle

The measured thermal interruption limits for the two nozzle materials in pure CO_2, shown in Figure 8, are (7.59 ± 0.22) A/µs and (7.92 ± 0.24) A/µs for PMMA and PTFE respectively. Results agree within the 2σ uncertainty.

This result, as well as the TTF shown in Figure 5, confirm that there is no difference caused by the material of the nozzle in the present experimental puffer

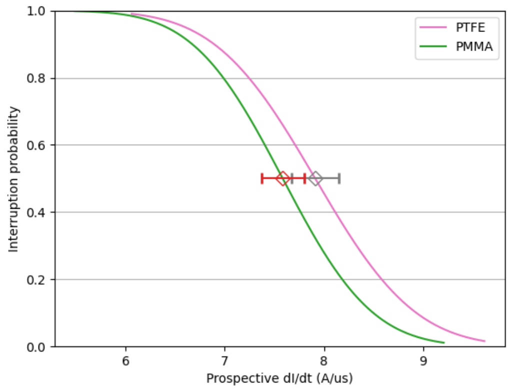

Figure 8. Thermal interruption performance of CO_2 with PMMA and PTFE nozzle

CB configuration. This is plausible, as we don't observe significant ablation (approximately 3% increase of nozzle throat cross-section over all 44 shots) and also no difference in pressure build-up. Consequently, there is no significant backheating, and therefore minimal ablated nozzle material is present in the blowing gas at CZ.

4. Conclusions

In this puffer CB experiment, the thermal interruption limit of CO_2/C_4F_7N mixture determined from 44 measurements was found to be (8.97 ± 0.26) A/µs at $\Delta p = 5.85$ bar. Extinction peaks were reported with a threshold value of around 1.2 kV. The thermal interruption limit of CO_2 was found to be (7.59 ± 0.22) A/µs which is an unexpectedly high difference in comparison to the limit of CO_2/C_4F_7N. A large number of failures in CO_2 were observed to be dielectric breakdowns within first 10 µs and were referred to as "hot dielectric" failures. Only one "hot dielectric" event was observed in CO_2/C_4F_7N. This different failure mechanism is relevant for test duties in which the TRV starts immediately after CZ and increases continuously with a high du/dt for more than a few µs, like in some SLF duties with the first line peak occurring even after more than 10 µs. In such cases, adding C_4F_7N to CO_2 may increase the interruption performance significantly. For test duties with less severe TRV in the first few µs, SLF-duties with very early first line peaks or terminal faults, this new failure mechanism will be less relevant (or not at all). The thermal interruption limit for CO_2 with PTFE and PMMA nozzles agrees within 2σ uncertainty. This confirms that the interruption performance is not influenced by the nozzle material in the present setup, and differences can be attributed to the gas (mixture) itself.

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