INVESTIGATIONS ON THE THERMAL INTERRUPTION CAPABILITY OF CO_2 IN NOZZLE SYSTEMS WITH TWO HEATING CHANNELS

P. G. NIKOLIC[1]*, M. WEUFFEL[1] AND A. SCHNETTLER[1]

[1] Institute for High Voltage Technology, RWTH Aachen University, 52056, Aachen, Germany
*nikolic@ifht.rwth-aachen.de

ABSTRACT

Circuit breakers and gas insulated switchgear (GIS) filled with SF_6 (sulphur hexafluoride) represent the state of the art in high voltage switching equipment. Nevertheless the discussion on climate change forces the search for possible SF_6 substitutes resulting in first CO_2 (carbon dioxide) filled circuit breakers and circuit breaker prototypes available. Therefore the optimization of the switching chamber for the thermal and thermodynamic properties of CO_2 is in the focus of this contribution. For this purpose nozzle systems with two heating channels supplied from two heating volumes are investigated. Their thermal interruption capability is determined at varying filling pressures from $p = 0.35$ MPa to 1 MPa and current amplitudes of $I_{peak} > 20$ kA. Here the maximum thermal interruption capability is found for an absolute filling pressure of $p = 1$ MPa. The experimental results are compared to those of CFD (computational fluid dynamics) simulations and first design criteria for switching chambers with two heating channels are determined.

1. INTRODUCTION

Nowadays SF_6 is widely used as insulating and arc quenching medium in high voltage circuit breakers and gas insulated switchgear. Nevertheless SF_6 is a strong greenhouse gas with a global warming potential of 22800 CO_2 (carbon dioxide) mass equivalents. Therefore the search for possible SF_6 substitutes is necessary in the context of political discussions on climate change. Additionally an increase of efforts needed for SF_6-handling-certification is expected with the revision of the European regulation of fluorinated gases. Due to its small arcing time constant, CO_2 is an option as quenching gas. As the dominating cooling mechanisms during current interruption vary with the applied quenching gas – which means convective cooling and maximum arc resistance build-up in the stagnation point region in case of CO_2 [1] –, the switching chamber has to be adapted to the properties of the quenching gas. Recent CO_2-filled circuit breaker prototypes are based on the self-blast technology with additional increased puffer volume [2]. Therefore a high amount of energy stored in the operating mechanism is required for generating the necessary pressure build-up for arc quenching which consequently increases the manufacturing costs. Adopting the switching chamber for the optimum utilization of the thermodynamic properties of the quenching gas can lead to a reduction of the required energy of the operating mechanism. Thus in this contribution nozzle systems with two heating channels supplied from two heating volumes are considered by experimental and simulative investigations.

2. EXPERIMENTAL APPROACH

In case of using CO_2 as quenching gas, the maximum resistance build-up is observed in the stagnation point region [1]. An improvement of the thermal interruption capability in CO_2 could be achieved by extending the stagnation zone and the corresponding cooling effect inside the nozzle system. The approach presented here is the construction of a switching chamber with two heating channels supplied from two heating volumes. In addition to this change in the flow design of the switching chamber, the thermodynamic properties of ablated PTFE (polytetrafluorethylene) from the insulating nozzles can be exploited for increasing the interruption performance in a second approach. These two constructive measures are applied to circuit breaker models in the context of this contribution. The cross-sectional views of both circuit breaker designs used are depicted in figure 1. DUT 1 (device under test) is equipped with a nozzle system made of PTFE providing two heating channels. For increasing the PTFE percentage in the quenching gas, DUT 2 is additionally equipped with elongated heating channels. The housing of both circuit breaker models is made of aluminium. The size of the heating volumes is designed to achieve similar blowing conditions from both volumes at current zero. Plug electrodes consisting of tungsten-copper (WCu) are used at the ground and at the high voltage potential side of the circuit breaker models.

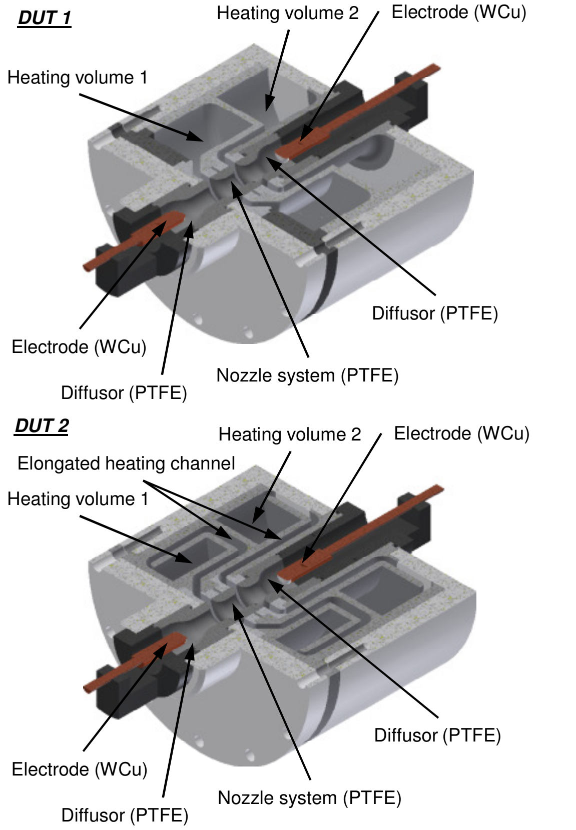

Fig. 1 Cross-sectional views of DUT 1 with two heating channels (top) and DUT 2 with elongated heating channels for increased PTFE percentage in the quenching gas (bottom).

Basic investigations on the influence of the blow gas pressure or of additional ablation elements in the heating volume on the thermal interruption capabilities are carried out in circuit breaker models with fixed contact distance up to now [3]. Nevertheless the transfer of these results to real circuit breakers with moving contact system requires the determination of the influence of the contact travel on the thermal interruption capability. Therefore additional investigations are performed with a third test device DUT 3. For the realization of the contact movement, one plug electrode is replaced by a tulip contact in DUT 1. As moving contact a plug contact is used and driven by a pneumatic operating mechanism achieving velocities in the range of v = 10 m/s. The resulting travel curve is depicted in figure 2.

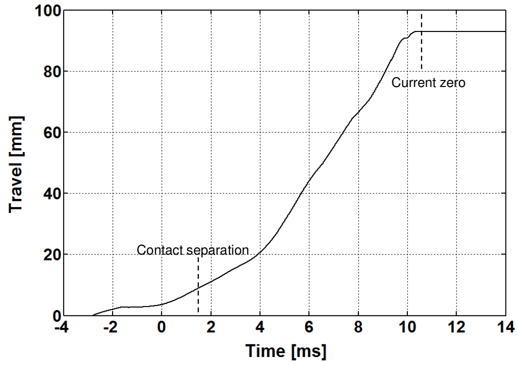

Fig. 2 Travel curve of the plug electrode in DUT 3 driven by a pneumatic operating mechanism.

The thermal interruption capability of all three test devices is determined by a synthetic Weil-Dobke test circuit according to figure 3. The DUT is first stressed by a high current from the high current circuit formed by a capacity of $C_H = 36$ mF and an inductance of $L_H = 315$ µH. Shortly before the zero crossing of the high current an injection current for emulating multiple zero crossings in the DUT is injected from the high voltage circuit consisting of $L_S = 2.51$ mH, $C_S = 11.56$ µF, $R_p = 800\ \Omega$, $C_p = 10$ nF and $R_E = 100$ MΩ. The amplitude of the test current during the high current phase (one sinusoidal half-oscillation) is adjusted to $I_{peak} = 22\ldots28$ kA to achieve a pressure build-up of $\Delta p_{CZ} = 1.2\ldots1.5$ MPa in the heating volumes at the current zero crossing. The experimental investigations are performed in CO_2 at absolute filling pressures of $p_{abs} = 0.35$ MPa, 0.5 MPa and 1.0 MPa.

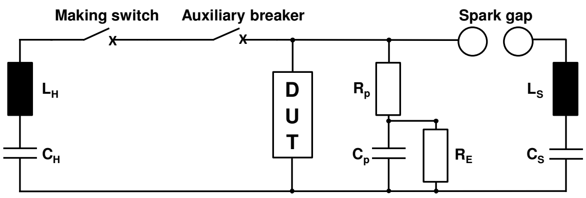

Fig. 3 Synthetic test circuit for the determination of the thermal interruption capability

3. EXPERIMENTAL RESULTS

From the results of the experimental investigations the thermal interruption capability of the different circuit breaker models can be determined. Therefore arcing voltage and current are measured with a high time resolution in the current zero region. Based on these measured values the thermal interruption capability di/dt_{limit} can be determined from the current steepness di/dt of each current zero and the resistance R_{200} determined 200 ns before current zero [4].

$$\left(\frac{di}{dt}\right)_{limit} = \frac{1}{k} \cdot \sum_{i=1}^{k} \left[\left(\frac{di}{dt}\right)_{Measurement,i} \cdot \left(\frac{R_{200,i}}{R_{crit}}\right)^{\frac{1}{m}} \right]$$

Here the index m describes the relationship between R_{200} and di/dt [4]. The boundary between successful and non-successful current interruption is defined by the critical resistance R_{crit}. The resulting thermal interruption capabilities di/dt_{limit} for DUT 1 and DUT 2 in dependency of the filling pressure are depicted in figure 4 (cf. [3]). The results presented are recorded at an electrode distance of g = 89 mm i.e. with the plug electrodes placed in the diffusors of the nozzle systems (see figure 1).

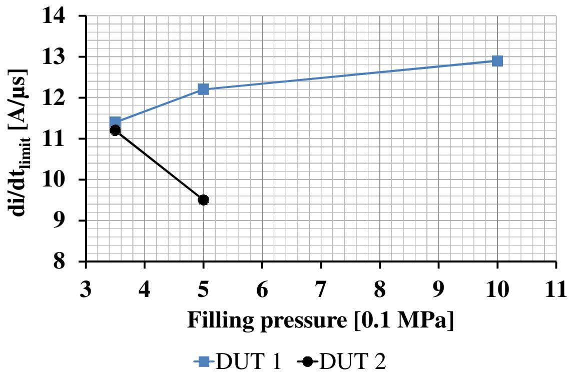

Fig. 4 Thermal interruption capability di/dt_{limit} for DUT 1 and DUT 2 for varying filling pressures (cf. [3])

For DUT 2 a significant decrease of the thermal interruption capability is found with increasing filling pressure, despite the increased percentage of PTFE in the quenching gas. On the contrary an increase of the interruption capability is observed for DUT 1 leading to a maximum at p_{abs} = 1.0 MPa. Nevertheless the variation of the interruption capability is in the range of 5% to 6% for $p_{abs} \geq 0.5$ MPa. Therefore no significant change of the interruption capability is expected for DUT 3 in this pressure range, too and the influence of the contact movement is only investigated for p_{abs} = 1.0 MPa (see also [5]). The position of the moving plug contact is adjusted to g = 74…84 mm from the tulip contact at current zero, i.e. also at the diffusor opening. Thus the investigated contact distance is in agreement with typical contact distances in circuit breakers at current zero which are in the range of 70 mm to 100 mm [5]. From figure 5 a decrease of approximately 15% compared of the thermal interruption capability of DUT 3 compared to DUT 1 is found.

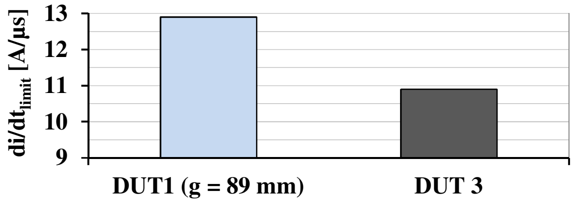

Fig. 5 Thermal interruption capability di/dt_{limit} for DUT 1 and DUT 3 at a filling pressure of p_{abs} = 1.0 MPa.

4. DISCUSSION

During the experimental investigations the highest thermal interruption capability is observed for DUT 1 at a filling pressure of p_{abs} = 1.0 MPa. This can be explained by the improved mixing of ablation gas from the nozzle system and the cold quenching gas in the heating volume compared to DUT 2, which is equipped with elongated heating channels. By this constructive measure the percentage of ablated PTFE in the blow gas is increased on the one hand. On the other hand the elongated heating channels inhibit the mixing of ablation gas and cold gas in the heating volume. From CFD simulations temperatures in the range of T = 7000 K…10000 K between the heating channels are determined (cf. [3]). Nevertheless this cooling effect due to the increased PTFE percentage in the blow gas is not sufficient to improve the arc cooling. This results from the lack of gas mixing in the heating volume. In addition a decreased thermal interruption capability is observed comparing DUT 3 with moving contact system and DUT 1 with fixed contact system. This effect is caused by a blocking of heating channel 1 by the plug electrode during the contact movement which leads to a delayed pressure build-up in heating volume 1. Thus at current zero the blow gas pressure is reduced compared to DUT 1 leading to a reduced interruption performance. A possible countermeasure could be a connection between both heating volumes to achieve similar pressure build-up in both volumes. In addition to the necessary symmetrical distribution of the pressure build-up in both heating volumes, the ablation of the nozzle has to be considered for judging the interruption performance. With increasing number of short circuit interruptions, the cross-sectional area of the nozzle increases due to ablation of nozzle material resulting in a loss of blow gas pressure at current zero. The increase of the nozzle cross-sectional area per energy input can be determined from the measuring of the diameter of the cylindrically shaped section of the nozzles after each experiment and the corresponding energy input calculated from current and arcing voltage. The results are depicted in figure 6 for DUT 1 for an electrode distance of g = 89 mm. From figure 6 an increase of the nozzle widening after the first experiment is observed due to increased ablation.

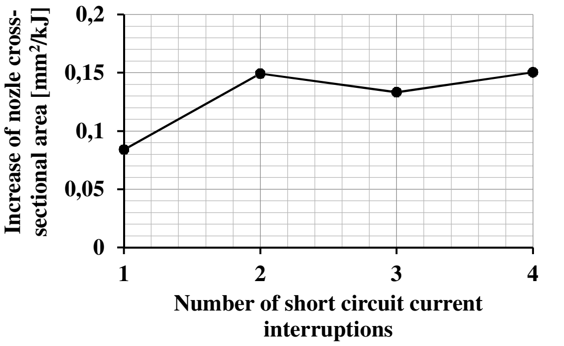

Fig. 6 Increase of the nozzle cross-sectional area in dependency of the number of short circuit interruptions

A possible explanation for this is the degradation in the depth of the nozzle material during the first current interruption followed by increased ablation during the next current interruptions due to the affection of the nozzle material. The effect can also be observed from recordings of the nozzle surface after the experimental investigations according to figure 7 and has to be considered for the design of a circuit breaker if e.g. a number of 10 short circuit current interruptions shall be achieved.

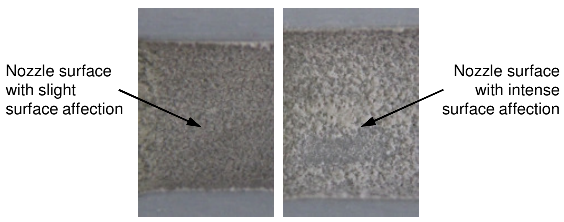

Fig. 7 Recordings of the nozzle surface after one (left) and after multiple current interruptions (right)

5. SUMMARY AND OUTLOOK

In this contribution the thermal interruption capability of CO_2 was investigated with circuit breaker models with fixed and moving contact system. It was observed that an increase of the PTFE percentage in the quenching gas does not necessarily lead to an improved interruption performance. A nozzle system with two short heating channels provides the highest interruption performance at a filling pressure of $p_{abs} = 1.0$ MPa due to the mixing of ablated nozzle material and cold gas in the heating volume. The comparison to a circuit breaker model with moving contact system shows that an equal arc blowing from both heating volumes improves the thermal interruption performance. Additionally the increase of the nozzle cross-section has to be considered for the design of the switching chamber to guarantee sufficient pressure build-up for arc blowing even after a certain number of short circuit current interruptions.

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REFERENCES

[1] M C Tang, “Resistance distribution in switching arcs of self-blast circuit breakers at the current zero phase”, Ph.D. Thesis (in German), RWTH Aachen University, 2010.

[2] T Uchii et al., “Fundamental Research on SF_6-free Gas Insulated Switchgear Adopting CO_2 Gas and Its Mixtures”, Proceedings of International Symposium on EcoTopia Science 2007 (ISET 2007), pp. 516-520, 2007.

[3] P G Nikolic, M Weuffel, A Schnettler, “Optimierung des Schaltkammerdesigns zum Einsatz von Kohlenstoffdioxid als Löschgas”, GIS-Anwenderforum, Darmstadt, Germany, 2013.

[4] C M Franck, M Claessens, H Nordborg, M Seeger et al., “Thermal Interruption Behaviour of High-Voltage Circuit Breakers”, XV International Conference on Gas Discharges and their Applications, Toulouse, France, 2004.

[5] P C Stoller, M Seeger, A Iordanidis, G V Naidis, “CO_2 as an Arc Interruption Medium in Gas Circuit Breakers”, IEEE Transactions on Plasma Science, vol. 41, pp. 2359-2369, 2013.