Design and Test of a Technology Demonstrator for a CO_2 Filled Circuit Breaker with Two Heating Volumes

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The revision of the European regulation on fluorinated greenhouse gases revived the search for possible SF_6 (sulphur hexafluoride) substitutes as arc quenching and insulating medium in high voltage gas circuit breakers and gas insulated switchgear. Nevertheless an objective evaluation of possible SF_6 alternatives requires a deep knowledge and understanding of the physical and technical limits of these technologies. In previous investigations the thermal interruption capability of the possible substitute CO_2 (carbon dioxide) was investigated by means of circuit breaker models. By comparison with computational fluid dynamics simulations design criteria for circuit breakers filled with CO_2 are determined in this research work. Based on these a technology demonstrator of a circuit breaker is constructed for a short circuit current of I_{sc} = 25 kA_{rms} with a switching chamber adapted to the physical and thermodynamic properties of CO_2. Therefore a nozzle system with two heating channels supplied from two heating volumes is used. The thermal interruption capability of this CO_2 circuit breaker is experimentally investigated in a synthetic test circuit and the number of succeeding successful current interruptions is determined. Finally an outlook on the dielectric strength of the demonstrator is given based on simulative investigations and modelling.

Keywords: circuit breaker, SF_6 substitution, CO_2, technology demonstrator

1 INTRODUCTION

In state of the art high voltage gas insulated switchgear and circuit breakers SF_6 (sulphur hexafluoride) is used as insulating and arc quenching medium. Despite its outstanding thermal and dielectric properties, SF_6 is also a strong greenhouse gas with an atmospherical lifetime of approximately 3200 years [1,2]. Lately, the search for possible SF_6 substitutes has been revived in 2014 by the revision of the European regulation on fluorinated greenhouse gases and has led to the investigation of several gaseous substitution technologies (e.g. [3]). Independent of the used alternative insulating gas, the use of SF_6 substitutes requires an adaption of the switching chamber design of circuit breakers on the thermal and dielectric properties of the quenching gas. This research work focuses on CO_2 (carbon dioxide) as possible substitute. Thus the dominating effects for the cooling of the switching arc at current zero are determined from simulative and experimental investigations. Based on the gained results a technology demonstrator for a switching chamber with two heating volumes filled with CO_2 is constructed and its thermal interruption capability is investigated for a short circuit current of I_{sc} = 25 kA_{rms} [4].

2 EXPERIMENTAL SETUP

For the experimental characterization of the thermal interruption capability of CO_2 a synthetic test circuit according to Figure 1 is used. The tested model circuit breaker (DUT – device under test) is first stressed by a high short circuit current from the high current circuit. The high current circuit consists of 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 is generated by the high voltage circuit consisting of L_S = 2.51 mH, C_S = 11.56 µF, R_p = 800 Ω, C_p = 10 nF and R_E = 100 MΩ. This injection current allows the investigation of multiple current zero crossings in the DUT.

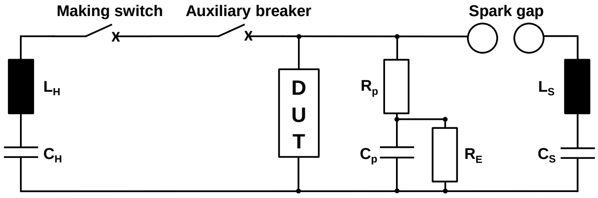

Fig.1: Synthetic test circuit

3 ARC COOLING IN CO_2

The thermal interruption capability, i.e. the capability of the quenching gas to interrupt the current at its zero crossing, of CO_2 in different circuit breaker models is investigated in detail in previous studies for arrangements with fixed and moving contact system (cf. e.g. [5]). These investigations focus also on arrangements with two heating channels supplied from two heating volumes multiplying the cooling effect in the stagnation point region [4,5]. Based on the experimental results the dominating influencing factors on the arc cooling and thermal interruption capability of CO_2 are determined in the following. Therefore at first the thermal interruption capability dependency on the average gas temperature inside the nozzle system at t = 10 μs before current zero is analyzed (cf. Figure 2). The temperature is analyzed at a radial distance of r = 3 mm from the symmetry axis of the circuit breaker models and results from CFD (computational fluid dynamics) simulations. The obtained temperature values are compared to the experimentally determined thermal interruption limit di/dt_{limit}. This analysis yields a limit of di/dt = 10.5…10.6 A/μs when going below a temperature value of T = 2000 K inside the nozzle system shortly before current zero. This dependency is valid for different switching chamber designs (one or two heating channels) and filling pressures. Besides the reduction of the gas temperature to values below T = 2000 K a successful arc cooling in CO_2 also requires a uniform blowing of the switching arc. This requirement results from the interaction between the switching arc and the blow gas at the arc boundary. In contrast to current interruptions in SF_6, in case of CO_2 the arc is not strongly quenched by the blow gas flow. Instead of this, convective cooling zones with a radial extension of several millimeters are established at the outer arc boundary. In this region the switching arc is cooled by convective cooling. An example for this cooling process based on simulation results is given in Figure 3. This kind of interaction between switching arc and insulating nozzle can be observed in the cylindrical nozzle parts as well as in the stagnation point region. The arc core boundary can be observed from the simulation results at a radial position of r ≈ 0.5 mm by analyzing the power density p_{ohm} caused by ohmic heating. From the convective cooling power density p_{conv} a radially extended cooling zone can be determined. In this cooling zone the arc temperature profile is smeared in the range of a few millimeters and the switching arc is cooled in its zero crossing by convective cooling. Thus next to reduction of the gas temperature to values below T = 2000 K the increase of the convective heat transfer in these cooling zones by a uniform blow gas flow is required for successful arc cooling in CO_2. The convective cooling can be adjusted by adequate flow design of the nozzle system and the heating volume of the circuit breaker.

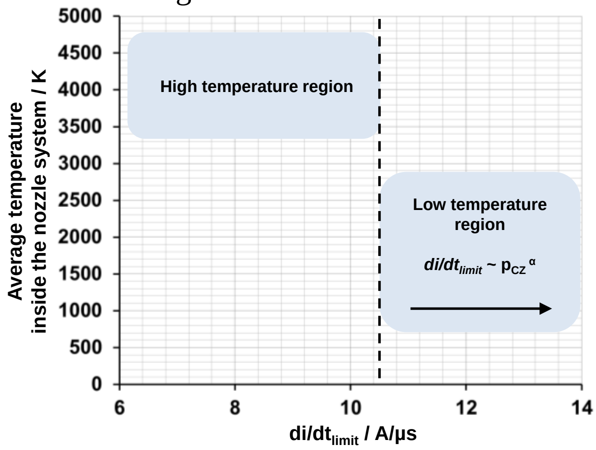

Fig.2: Temperature dependency of thermal interruption capability of CO_2 for a pressure build-up of Δp_{CZ} = 1.0…1.5 MPa

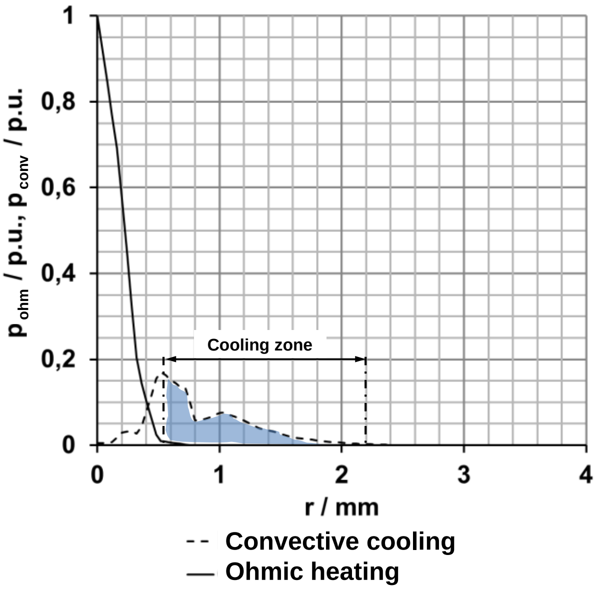

Fig.3: Simulated convective cooling zone for a switching arc in CO_2

4 DESIGN AND TEST OF A TECHNOLOGY DEMONSTRATOR

Based on the physical processes of arc cooling identified in the previous section a technology demonstrator according to Figure 4 is constructed. The technology demonstrator is designed for a short circuit of I_{sc} = 25 kA_{rms} corresponding to a thermal interruption capability of di/dt_{limit} = 11.1 A/µs. The switching chamber is equipped with a nozzle system made of PTFE (polytetrafluorethylene) and a contact system consisting of tungsten copper (WCu). The self-blast switching chamber is equipped with two heating volumes for establishing a uniform blow gas flow. The total heating volume equals to V = 1.4 l. The contact movement in the technology demonstrator is realized by a pneumatic operating mechanism which yields contact velocities of up to v = 10 m/s. The operating mechanism is connected to the plug electrode of the circuit breaker.

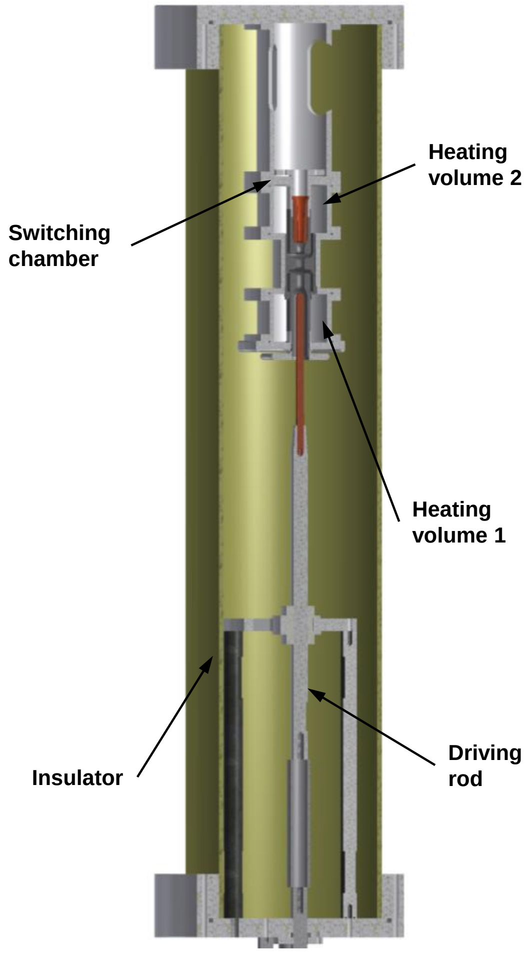

Fig.4: Schematic technical drawing of the technology demonstrator

The maximum contact gap is limited to g = 75 mm by the operating mechanism. In addition to that the nozzle system is designed to achieve a ratio of heating channel cross-sectional area to nozzle cross-sectional greater than 2.5 yielding uniform flow conditions [4]. By this the convective cooling at the arc boundaries can be supported (cf. Figure 3). The filling pressure of the technology demonstrator is selected to p_{abs} = 1.0 MPa. In order to verify the interruption performance of the technology demonstrator the synthetic test circuit according to Figure 1 is used. The technology demonstrator is stressed with its rated short circuit current multiple times. By this the maximum number of successful current interruptions is determined. The results of the experimental investigations are summarized in Table 1. During the experimental investigations the pressure build-up in both heating volumes is recorded.

Tab.1: Experimental results for the interruption performance of the technology demonstrator for short circuit current stress

	di/dt [A/µs]	du/dt [kV/µs]	$\Delta p_{CZ,HV1}$ [bar]	$\Delta p_{CZ,HV2}$ [bar]
1	11.4	6.4	14.2	15.0
2	11.7	6.2	17.1	17.8
3	11.6	6.1	14.3	15.8
4	11.3	6.0	17.0	16.7
5	10,9	5.8	14.5	14.2

The short circuit tests yield a maximum number of five successive short circuit current interruptions in the first current zero crossing. After five current interruptions the contact system of the technology demonstrator is worn. Thus the interruption performance is not limited by the wear of the nozzle system and the corresponding loss of blow gas pressure with increasing nozzle cross-sectional area. Nevertheless during the test an increase of the pressure build-up of approximately 20% after the first current interruption is observed. This is in agreement with previous investigations and results from the affection of the nozzle during the first current interruption by the arc radiation. The nozzle material is degraded in depth by the arc radiation leading to increased ablation during the subsequent current interruptions [5]. Additional experimental investigations show that the interruption of operating currents requires an additional compression volume to support the interruption process. Besides the thermal interruption performance of the technology demonstrators, the dielectric recovery of the gap between the contacts after the current interruption has to be investigated. Therefore in this research work, the dielectric recovery characteristics are calculated based on the streamer criterion, using the electrical field inside the nozzle system and the gas density and temperature from CFD simulations. The calculation results according to Figure 5 show the application potential of the developed switching chamber for rated voltages of $U_r = 145$ kV comparing the dielectric recovery characteristics to the requirements from the standards. Inside the nozzle system of the switching chamber field control electrodes are applied to reduce the field stress at plug and tulip contact. These results additionally indicate that the construction of a circuit breaker with $U_r = 420$ kV is possible with a series connection of two switching chambers. Nevertheless this requires the build-up of a prototype and experimental validation.

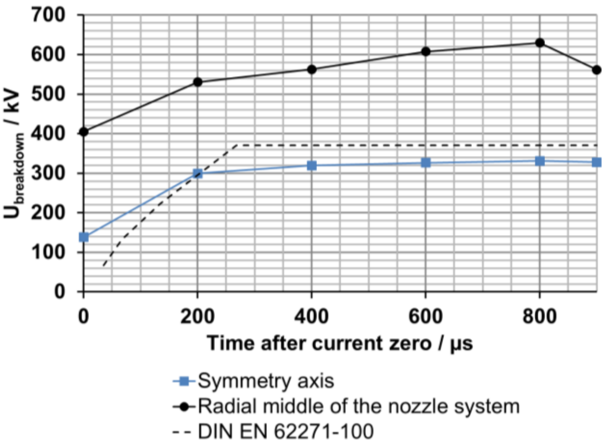

Fig.5: Dielectric recovery characteristics of the technology demonstrator calculated from CFD simulation results

5 CONCLUSION

In this research work a technology demonstrator for a circuit breaker using CO_2 as quenching gas was developed for a short circuit current of $I_{sc} = 25\ kA_{rms}$. Five successful short circuit current interruptions were possible with the developed switching chamber. In order to achieve this, the convective cooling of the switching arc has to be increased by uniform arc blowing and reducing the gas temperature inside the nozzle system below values of $T = 2000$ K. Additional calculations of the dielectric recovery characteristics of the switching chamber show the application potential for high voltage transmission grids. Here further tests are required.

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