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Dielectric Recovery Characteristics of High Voltage Gas Circuit Breakers Operating with CO_2 Mixture

Peng Lu, Branimir Radisavljevic, Martin Seeger, Daniel Over, Torsten Votteler, Bernardo Galletti

***Abstract*—**CO_2-based gas mixtures exhibit huge potential as the interruption medium for replacing SF_6 in high voltage switchgears. In this paper, the recovery characteristics of dielectric strength of CO_2-O_2 mixture in the post arc phase after the current zero are presented. As representative examples, the dielectric recovery curves under conditions of different gas filling pressures and short-circuit current amplitudes are presented. A series of dielectric recovery measurements suggests that the dielectric recovery rate is proportional to the mass flux of the blowing gas, and the dielectric strength recovers faster in the case of lower short circuit currents.

***Keywords*—**CO_2 mixture, high voltage circuit breakers, dielectric recovery rate, short-circuit current, mass flux.

I. Introduction

NOWADAYS, SF_6 is widely used as the insulation and arc-quenching medium in high-voltage switchgears due to its high dielectric strength and excellent arc interruption properties. However, since SF_6 is strong greenhouse gas with a global warming potential of about 23900 on a 100-year time horizon, the search for possible alternatives has drawn significant attention and been accelerating in recent years [1], [2]. In the narrow candidate range of dielectric gases, CO_2 -based gas mixtures exhibit huge potential for replacing SF_6 in high voltage switchgears [3]. The research on the dielectric withstands and current interruption of CO_2 mixtures has gained increasing attention in recent decades [4], [5].

Arc extinguishing in the vicinity of the current zero and dielectric recovery in the post arc stage are two crucial phases for a successful current interruption process in high voltage circuit breakers. After current zero, to prevent the dielectric reignition, the recovery rate of the dielectric strength of the hot gas in the arcing zone must be faster than the rise-rate of the transient recovery voltage across breakers. By far, although the dielectric characteristics of CO_2 mixtures under the ambient temperature and static conditions has been published with the increasing number, there is still little number of studies reporting on the dielectric recovery characteristics of CO_2 mixtures after arcing [6]. In this paper, the dielectric recovery characteristics of CO_2-O_2 mixture in the post arc phase is presented. The dielectric recovery curves under conditions of different gas filling pressures and short-circuit current amplitudes are compared. The dependence of the dielectric recovery rate on the mass flow rate are discussed.

II. Experiment

A. Test Device

A test device based on a representative circuit breaker geometry [7] is used for the measurement of the dielectric strength recovery. Fig. 1 shows the main components of the general test device, which consists of the moving contact (tulip), fixed contact (plug), PTFE nozzles, heating volume (HV) and compression volume (CV).

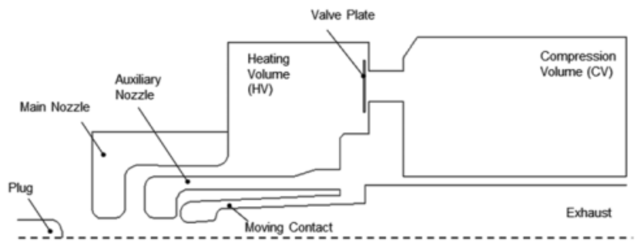


Fig. 1 Schematic drawing of the test device [7]

The nominal contacts are not shown here. The moving contact (tulip), which is mounted on the puffer rod, is driven by a motor drive. The moving of the puffer cylinder against a fixed piston generates the mechanical pressure build-up in the CV and HV. HV is directly connected to the arcing zone through a channel. During arcing, when the arc induced pressure build-up is higher than the mechanical pressure build-up, the back-heating occurs, the hot gas in the arcing zone flows back into the HV to help the pressure build-up in the HV. With the strong back-heating, e.g., in case of high current tests, a one-way valve (named as intermediate valve) between the HV and the CV closes, which boosts pressure build-up in the HV. In case of the low current condition, the pressure induced by the arc is low and it only induces the nozzle clogging effect. In such situation, the pressure in the HV is mainly built up mechanically. In this paper, the dielectric recovery is measured under the condition of the low current, i.e., less than 18 kA of the peak current. In the tests, piezo-resistive pressure transducers (Kistler, 200 mV/0.1 MPa) were connected to the HV and the CV to monitor the pressure build-up. The displacement of the moving contact side is determined using a position-sensitive potentiometer. In this paper, the test device was filled with 10 bar mixture of CO_2 and O_2 in most tests. Only in tests with lower gas filling pressures, i.e., Section III *B*, the test device was filled with 5 bar

Peng Lu is with Hitachi Energy Research, Hitachi Energy, Aargau 5405 Baden-Dättwil, Switzerland (corresponding author, e-mail: peng.lu@hitachienergy.com).

Branimir Radisavljevic and Martin Seeger are with Hitachi Energy Research, Hitachi Energy, Aargau 5405 Baden-Dättwil, Switzerland (e-mail: branimir.radisavljevic@hitachienergy.com, martin.seeger@hitachienergy.com).

and 2.5 bar CO_2-O_2 mixtures. In all tests, the partial pressure ratio between CO_2 and O_2 is the same, i.e., 9:1. Fig. 2 shows typical waveforms of the travel curve, current and pressure build-up (Δp) in the HV and CV during an opening operation of the test device. The arcing time is about 17.7 ms.

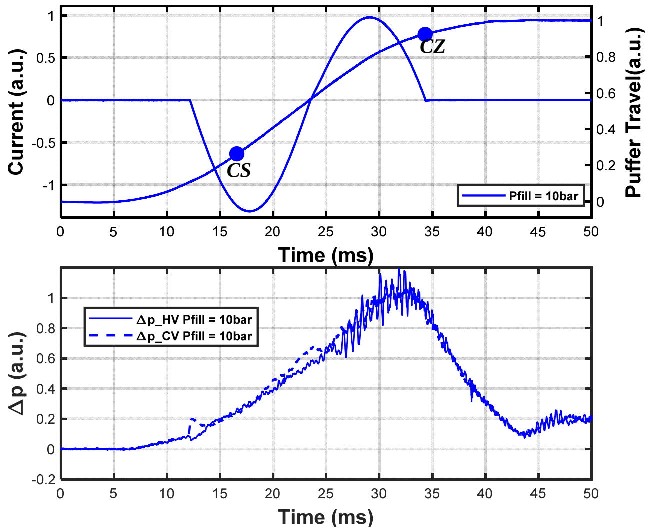


Fig. 2 Typical waveforms of travel curve, *SC* current and pressure build-up (Δp) in the HV and CV. *CS* denotes Contact Separation, *CZ* denotes Current Zero. Arcing time is about 17.7 ms. $t = 0$ indicates the starting time of the puffer movement

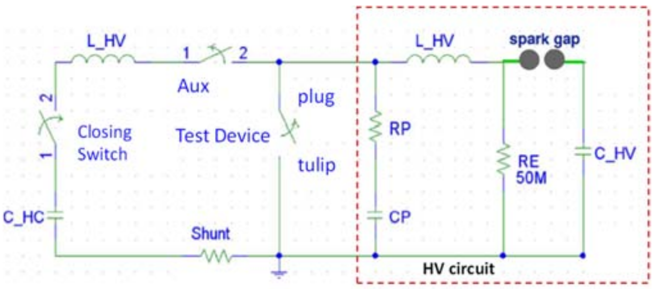


Fig. 3 Sketch of the synthetic test circuit for the dielectric recovery measurement

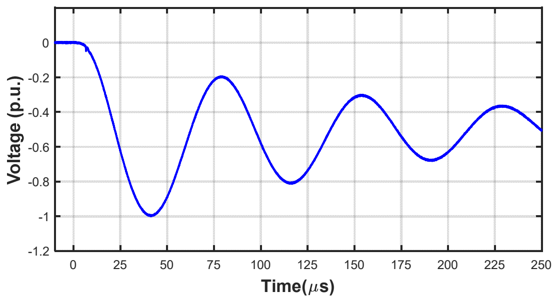


Fig. 4 Waveform of the transient recovery voltage

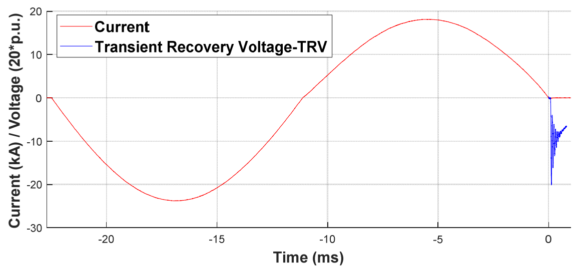
B. Synthetic Test Circuit

Fig. 3 shows the sketch of the synthetic test circuit for dielectric recovery measurements. The short-circuit (*SC*) current is generated by a *LC* oscillatory circuit, which can deliver an *AC* current with an adjustable amplitude and a halfwave duration of about 10~12 ms. In this paper, the dielectric recovery was measured under two peak current levels, i.e., about 18 kA and 6.5 kA. The right-hand part is a high voltage injection circuit, which applies the transient recovery voltage (*TRV*) to the test device after *CZ*. *TRV* has a negative polarity, as shown in Fig. 4. The fixed contact (plug) is connected to the high voltage potential, the moving contact (tulip) is on the ground side. In this paper, the relative voltage unit is used, i.e., p.u., which is relative to the peak value of *TRV*. The application of *TRV* is controlled by a spark gap (*SG*). The triggering of *SG* is synchronized with the final current zero instant of the *SC* current by a time delay unit. After the current interruption, *TRV* is applied to the test device at different time delays (5 µs to 400 µs) after the final current zero. Following this procedure, the recovery characteristic of the dielectric withstand and breakdown is obtained by scanning the delay time. The *SC* current through the test device is measured by a shunt resistor, the voltage across the test device is measured by a capacitive-resistive voltage divider. The waveforms are recorded by LeCroy digital oscilloscopes.

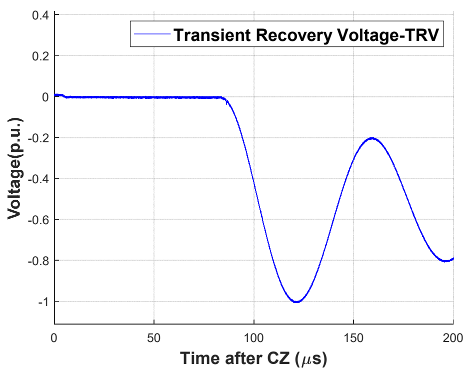
III. Results and Discussion

A. Waveforms of Dielectric Recovery Measurement

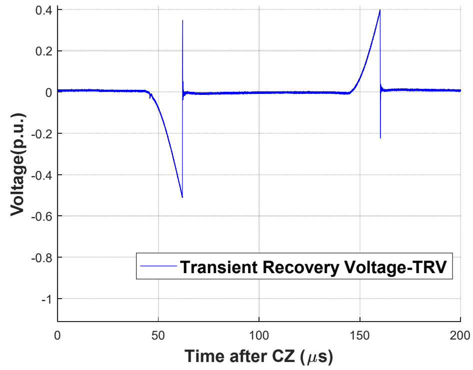
Fig. 5 (a) shows the typical waveforms of *SC* current and the *TRV*, which is applied to measure the breakdown voltage in the post arc phase after *CZ*. Figs. 5 (b) and (c) show example cases of dielectric withstand and breakdown. In Fig. 5 (b), *TRV* was applied at about 96 µs after *CZ*, the breaker withstood the *TRV*. In Fig. 5 (c), *TRV* was applied at 44 µs after *CZ*, the breakdown occurred at the voltage level of about 0.5 p.u.



(a)



(b)



(c)

Fig. 5 (a) Waveforms of *SC* current and *TRV* applied after *CZ*, examples cases for dielectric withstand (b) and breakdown (c)

B. Effect of Gas Filling Pressure on the Dielectric Recovery Rate

Fig. 6 shows the recovery curve of dielectric strength after *CZ* for CO_2 mixtures with different gas filling pressures. The higher gas filling pressure generates a higher stagnation pressure for cooling the arc and removing the hot gas in the post arc phase, which facilitates the dielectric recovery process. To see a significant dependence of the dielectric recovery on the stagnation pressure, tests with lower filling pressures, i.e., 5 bar and 2.5 bar were performed. The dielectric recovery curves exhibit two distinct phases [8]. First, immediately after *CZ*, the breakdown voltage rapidly rises until about 50 µs after *CZ*. Here, this phase is named as the first recovery phase. Afterwards, the dielectric recovery process slows down and finally reaches a plateau. The rise of dielectric strength (breakdown voltage) in the first recovery phase approximately follows a linear way, which is described as the dielectric recovery rate 'du/dt' in this paper. It is seen that the higher gas filling pressure leads to a faster du/dt and eventually reaches a higher dielectric strength.

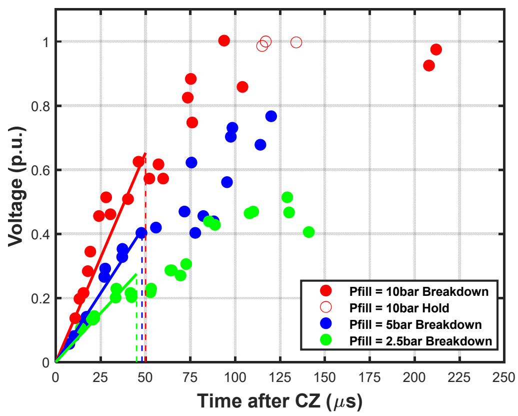


Fig. 6 Recovery curve of dielectric strength after *CZ* for CO_2 mixtures with different gas filling pressures. $t = 0$ indicates the *CZ* instant. The voltage amplitude is in per unit, p.u., which is relative to the peak of *TRV* applied in the test

C. Effect of SC Current Amplitude on the Dielectric Recovery Rate

Fig. 7 compares the dielectric recovery process for *SC* currents of ~18 kA and 6.5 ~kA. The gas filling pressure for these tests were same, i.e., 10 bar. The breakdown voltage level recovers faster after *CZ* of a lower *SC* current. The dielectric recovery rate 'du/dt' in case of ~6.5 kA current is about 1.6 times as the case of ~18kA current. It is noted that for 6.5 kA and 18 kA *SC* currents, the stagnation pressures at *CZ* are similar.

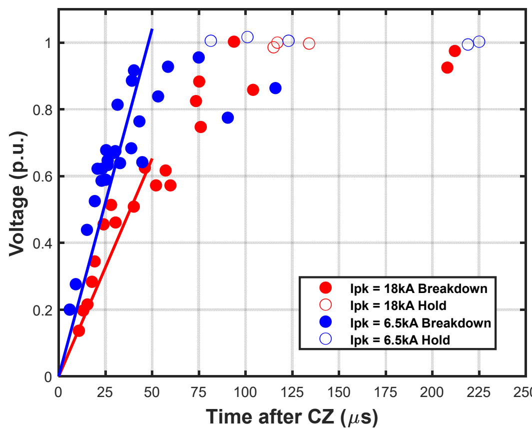


Fig. 7 Recovery curve of dielectric strength after *CZ* for *SC* current of 18 kA and 6.5 kA. $t = 0$ indicates the *CZ* instant. The voltage amplitude is in per unit, p.u., which is relative to the peak of *TRV* applied in the test

D. Dependence of the Dielectric Recovery Rate on the Mass Flux of the Blowing Gas

The dielectric strength of a gas is proportional to its particle number density or mass density. For circuit breakers, after the *CZ,* the recovery of the dielectric strength depends on the gas density recovery in the post arc phase, which is proportional to the mass flow rate through the nozzles. The dielectric recovery rate is then described by $du/dt \sim dm/dt$. The average mass flux was computed for 18 kA *SC* current, by the computational fluid dynamics (CFD) simulation, which is based on Ansys Fluent solver and an in-house developed UDF library for circuit breaker-relevant arc physics [9]. Fig. 8 shows that the *du/dt* is proportional to the mass flux through nozzles. Those two low du/dt points in Fig. 8 correspond to the tests with filling gas pressures of 2.5 bar and 5 bar in Fig. 6.

By designing different arcing zone geometries and performing a series of dielectric recovery measurements, the dependence of the dielectric recovery rate on the relative mass flux was plotted for *SC* currents of ~18 kA and 6.5 ~kA. Here, the relative mass flux is the mass flux which is normalized to the mass flux at the blowing gas pressure of 15 bar. Fig. 9 shows that the dielectric recovery rate is proportional to the mass flux, which agrees with Fig. 8. The dielectric strength recovers faster in case of lower *SC* current, i.e., 6.5 kA here.

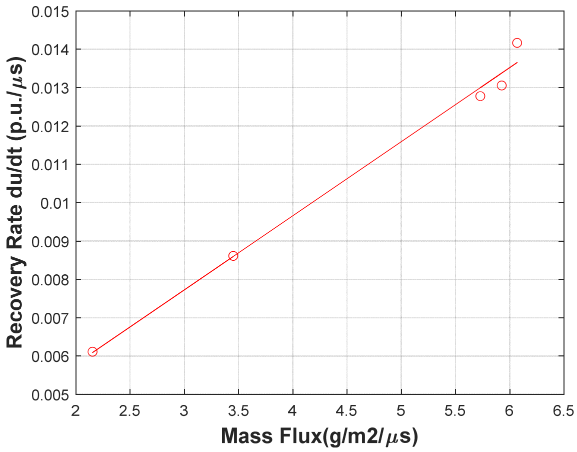


Fig. 8 Dielectric recovery rate versus simulated mass flux through nozzles in case of 18 kA *SC* current

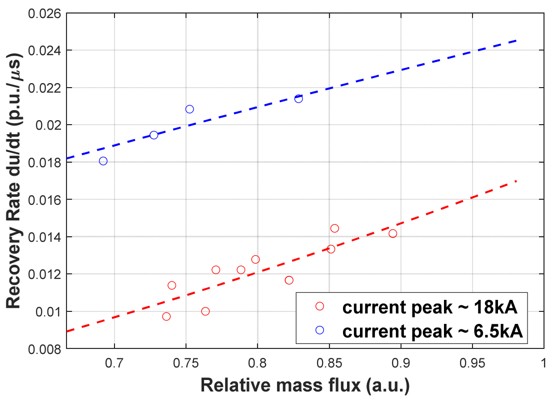


Fig. 9 The dependence of dielectric recovery rate on the relative mass flux. Dash lines are fitted by the power scaling law. Blue line is fitted for the 6.5 kA SC current, red line is fitted for the 18 kA SC current

IV. Conclusion

The recovery characteristics of dielectric strength of CO_2-O_2 mixture in the post arc phase after the current zero are investigated. The dielectric recovery curves were measured and compared under conditions of different gas filling pressures and different short-circuit (*SC*) current amplitudes. The dielectric recovery rate scales linearly to the mass flux of the blowing gas at the current zero instant. A lower short circuit current leads to a faster recovery process of the dielectric strength in the post-arc phase.

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