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ARC VOLTAGE AS AN INDICATOR OF NOZZLE ABLATION DEGRADATION IN HIGH-VOLTAGE CO2 GAS CIRCUIT BREAKERS

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Abstract. Energy released by electric arc during short-circuit current interruption is mostly absorbed by the surrounding cold gas and partly transferred to the arcing contacts and nozzle. The radiation is the main mode of thermal energy transfer between the electric arc and nozzle surface. Experimental research on the nozzle ablation has been carried out at a model circuit breaker, in which CO_2 is filled in the chamber and poly-tetrafluoro-ethylene (PTFE) is used as the nozzle material. It is found that the arc voltage can be as an indicator of nozzle ablation degradation by comparing the voltage at current peak and arc voltage extinction peak. Under 20 kA and 35 kA peak current interrupting conditions, the voltage at current peak decreases with the number of operations. There are two factors that affect the arc voltage at current peak. One is the size of the arc cross section, and the other is the content of PTFE entering the arc zone, which affects its conductivity.

Keywords: circuit breaker, CO_2, electric arc, nozzle ablation.

1. Introduction

High voltage circuit breaker (HVCB) is a key switching element to protect the power system against various faults, and its current carrying capacity and interrupting capacity are of prime importance. Arc-extinction chamber plays an important role in the abnormal or fault current interruption. Nozzles, mainly made of poly-tetrafluoro-ethylene (PTFE), are exposed to switching arc radiation directly during current interrupting operation. Nozzle ablation has dual positive and negative effects on current interrupting capability in HVCBs [1]. On the one hand, pressure built-up is generated when the ablated PTFE vapour heats up and compresses the gas in the expasion chamber [2]. One the other hand, the throat diameter and the cross-section area of gas channel will increase after each current interruption, which reduces the current interrupting capacity of HVCBs [3]. Therefore, it is essential to monitor the interruption chamber effectively and assess the nozzle condition to prevent probable failures and predict the lifetime of HVCBs [4].

The electrical degradation of contacts and nozzles inside the interruption chamber has been extensively investigated in term of mass loss, physical change and the pressure build-up process in the experimental aspect. In order to estimate the remaining lifetime and the allowable number of interruptions of HVCBs, there are some engineering methods based on the availability of the peak current amplitude, transferred electric charge, arc energy and the gas pressure [5–9].

In this contribution, experimental research on the nozzle ablation has been carried out in a high-voltage CO_2 gas circuit breaker (GCB). By comparing the voltage at current peak and arc voltage extinction peak, it is found that the voltage at current peak can be as an indicator of nozzle ablation degradation under fault current (amplitude of 20/35 kA) conditions in high-voltage CO_2 GCB.

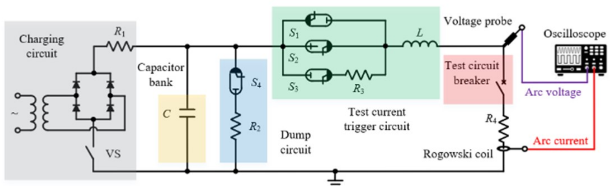

Figure 1. Schematic diagram of the main circuit.

2. Experimental investigation

2.1. Setup

The testing circuit breaker unit is a modification of a 245 kV/40 kA live tank self-blast HVCB. In Figure 1, the main circuit of the experimental system is composed of a charging circuit, a capacitor bank, a dump circuit, a test current trigger circuit and a test circuit breaker. The capacitor bank is used as the power source of the arcing current, which has a capacitance of 35 mF, a maximum charging voltage of 6.3 kV and a maximum stored energy of 695 kJ. There are four ignitrons to turn the current on or off in the main circuit, which are the dump ignitron, DC ignitron, forward and reverse AC ignitrons. An ignitron is a gas-filled tube used to control the current in a circuit. The arc voltage and current are measured using a high voltage probe (Tektronix P6015 A) and a Rogowski coil respectively, and the data is recorded by a digital oscilloscope (Tektronix DPO 2024).

In order to explain the opening process in the interruption chamber during arcing test, the relative position between contacts and nozzle is given in a schematic diagram (Figure 2). In a real HVCB, the

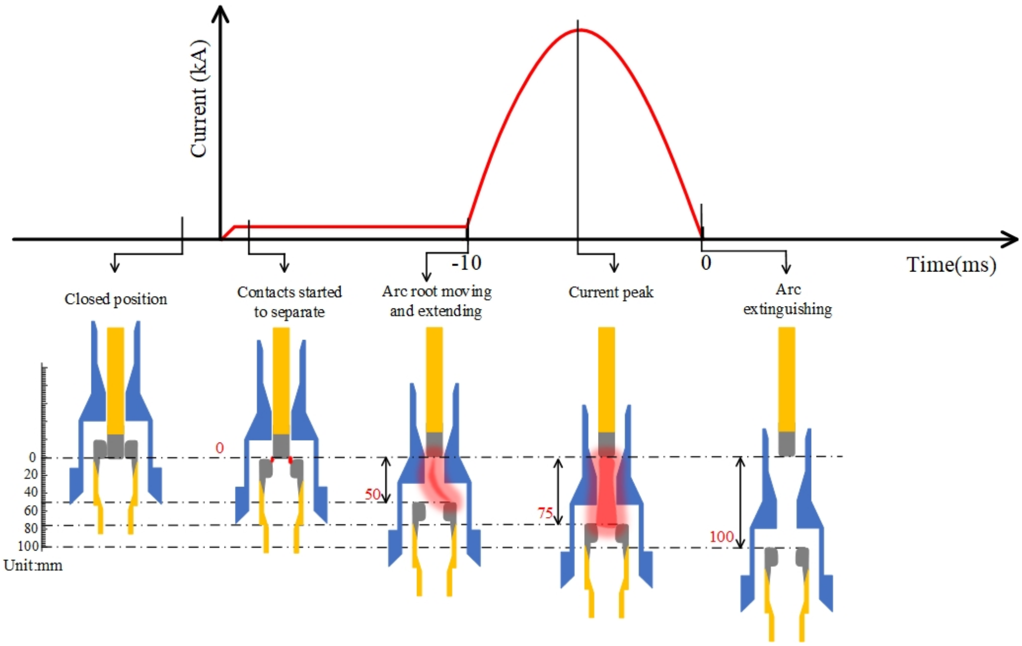

Figure 2. Schematic diagram of relative position between contacts and nozzle during arcing test.

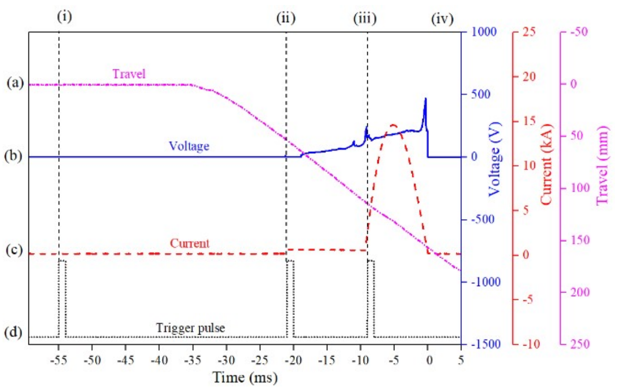

Figure 3. Timing of trigger pulses and the waveforms, (a) travel, (b) voltage, (c) current, and (d) trigger pulses - (i) trigger for hydraulic mechanism, (ii) trigger for DC current, and (iii) trigger for half-cycle AC current.

interrupting time consists of relay time, opening time and arcing time. Under different fault current interrupting conditions, the arcing time is varied from less than half cycle to several cycles of current. In order to realize the ablation effect of the switching arc on the nozzle as much as possible, it is necessary to generate a small DC to sustain the arc. Until the plug contact is located at the outlet of the nozzle throat, a large AC current is generated, and the nozzle wall is completely exposed to high-energy arc radiation.

The timing of trigger pulses and the typical waveforms (i.e., arc voltage, arc current and travel) are shown in Figure 3. At the beginning of arcing test, the first trigger pulse is issued to trigger the driving mechanism and the digital oscilloscope simultaneously. Before the arcing contacts are separated, the second trigger pulse should be issued to trigger the DC ignitron, and a low and slowly decaying DC current passes the arcing contacts and maintains an arc for tens of milliseconds. At a certain point in time after contact separation, the third trigger pulse is issued to trigger the forward AC ignitron. A positive half cycle AC current then replaces the DC current. The arc is extinguished automatically at the first current zero crossing point. Finally, the dump ignitron is triggered and the remaining charge in the capacitor bank is discharged through a resistor.

2.2. Experimental results

The measured arc voltage and current at three different current levels (peak current amplitudes of 5/20/35 kA) are shown in Figure 4. Five consecutive arcing tests were carried out to observe electrical degradation behavior and evaluate the degree of nozzle ablation. In order to display the arc voltage and current information as completely as possible, the arcing test is divided into two stage, namely high current interval and current-zero interval. The volage at current peak and arc voltage extinction peak are selected to present the high current and current-zero periods, which are shown in Figure 5.

Under 5 kA arcing condition, the arc voltage increases with the contacts seperation and the axially blown arc is stabilized by convection. The nozzle is not subject to arc ablation due to the relative small arc energy. When current increases to 20 kA and 35 kA, the arc status is transferred from axially-blown to ablation-controlled arc, which is a type of convectively cooled arcs by arc-induced wall vaporization. There is a hysteresis phenomenon in the arc voltage reaching the maximum value during the high-current stage.

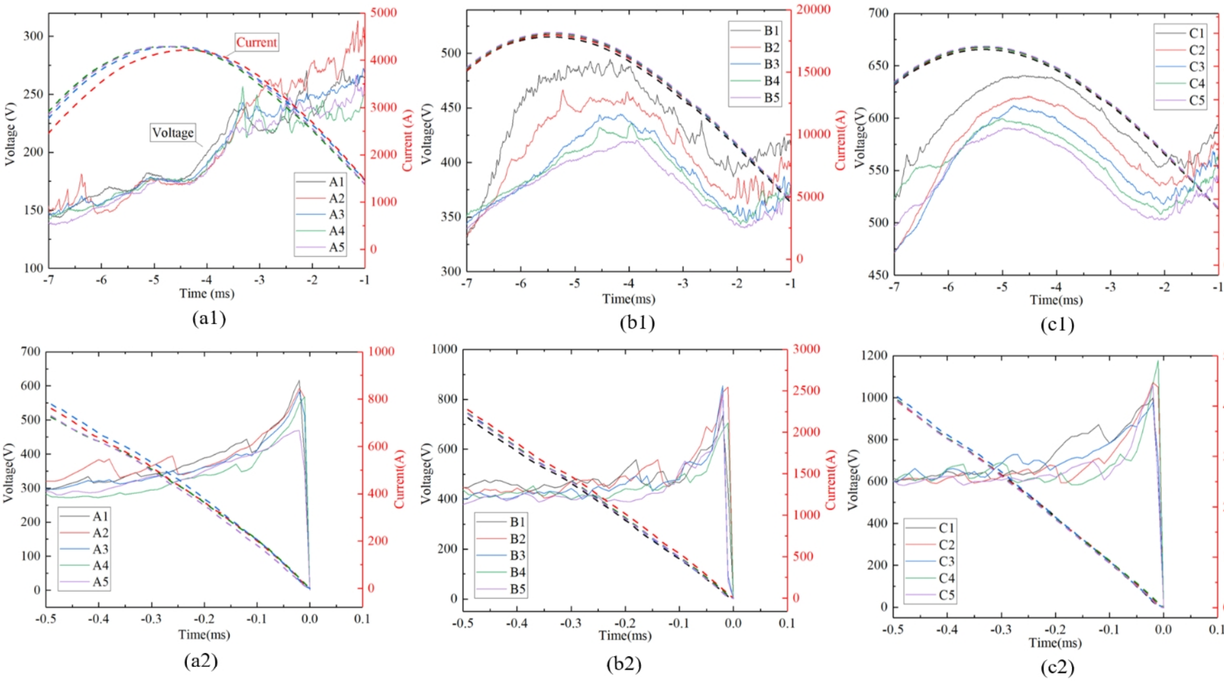

Figure 4. Voltage and current waveforms during arcing period and cloze to current-zero point (a) Small current level (5 kA); (b) Medium current level (20 kA); (c) Large current level (35 kA).

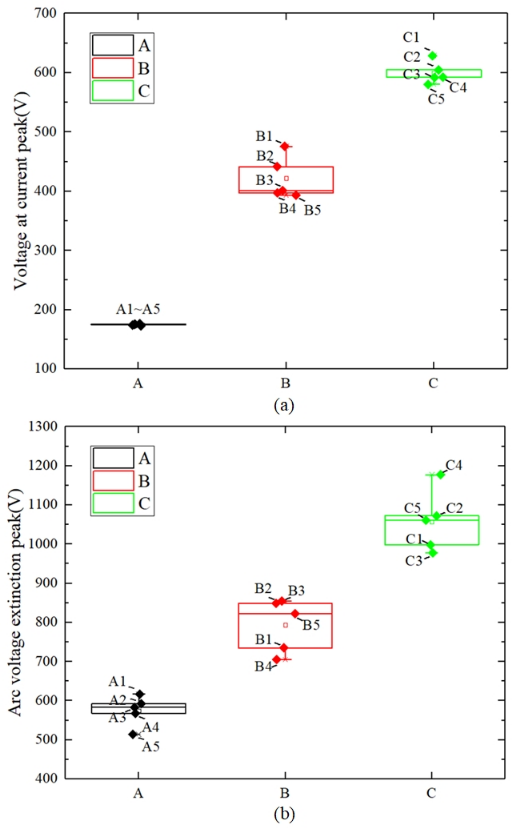

Figure 5. (a) Voltage at current peak; (b) Arc voltage extinction peak under different current conditions (A-5 kA; B-20 A; C-35 kA).

3. Discussion

In order to compare the difference between voltage at current peak and arc voltage extinction peak, the change process of the arc voltage with the number of operations under 5/20/35 kA arcing tests is shown in Figure 6. Under 5 kA current peak condtion, the voltages at current peak are almost the same, but the arc voltage extinction peak shows a decreasing trend with each test, which is related to the amount of metal vapor injected into the arc after each contact erosion. Under 20 kA and 35 kA current peak conditions, the voltage at current peak has a downward charateristic with the sequence of operations. However, the arc voltage extinction peak are scattered randomly.

Arc voltage can be calculated from Ohm's law

$$U_{\mathrm{arc}} = \frac{L_{\mathrm{arc}}}{\sigma\left(T\right) \cdot S_{\mathrm{arc}}} \cdot i, \tag{1}$$

where U_{arc} is the arc voltage (V), L_{arc} is the arc length (m), S_{arc} is the cross-sectional area of arc (m^2), $\sigma\left(T\right)$ is the electrical conductivity as a function of gas temperature (S/m), and i is the current (A).

During high-current period, nozzle wall is exposed to strong arc radiation and PTFE will enter the arc zone when the nozzle material is vaporied. The arc temperature and electrical conductivity will change with the different content of PTFE. After each shot at 20/35 kA arcing tests, the diameter of nozzle throat will increase. Therefore, the voltage at current peak is determined by $\sigma\left(T\right)$ and S_{arc}.

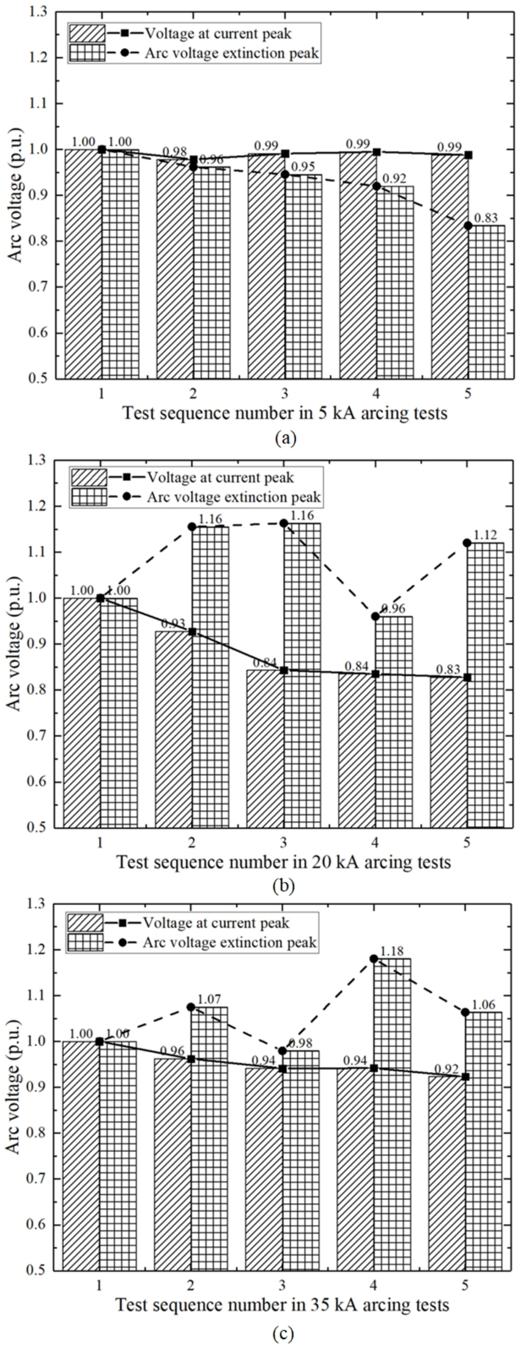

Figure 6. Voltage at current peak and arc voltage extinction peak (voltage of the first test as the reference value) according with test sequence number under (a) 5 kA; (b) 20 kA; (c) 35 kA arcing tests.

4. Conclusion

In this contribution, arc ablation experimental study of high-voltage CO_2 GCB has been done at three different peak current levels (5/20/35 kA). At each current level, five consecutive arcing tests were carried out to oberve the degradation behavior of nozzle ablation. Voltage at current peak and arc voltage extinction peak were selected to present the high-current and current-zero periods respectively. It is found that the voltage at current peak decreases with the number of operations under 20/35 kA current interrupting conditions. There are two factors that affect the arc voltage at current peak, which are first the size of the arc cross section and secondary the content of PTFE entering the arc zone during the process of melting and vaporization of nozzle material. More quantitative experimental measurements and theoretical calculations of mass loss of nozzle will be carried out in the future.

Acknowledgements

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