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PROPERTIES OF VACUUM ARC INFLUENCED BY ELECTRODE DIAMETER AND MATERIAL IN TMF CONTACT BASED ON FORCED CURRENT ZERO

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Abstract. With the increase in electrical equipment in More/All Electric Aircraft, 270V dc power supply systems will be needed. One method for DC interruption is forced current zero (FCZ). Based on FCZ technology with transverse-magnetic-field (TMF) contact, the spiral-type contacts are designed. Experiments with different currents are carried out with contact diameters being 30 mm, 40 mm, and 50 mm, and arcing surface materials Cu-W80 alloy and Cu-Cr50 alloy respectively. It is indicated by the experimental results that breaking capacity of vacuum interrupter and vacuum arc appearance are closely related to the electrode diameter and material. For the same size of electrode diameter, the breaking capacity in Cu-Cr50 is better than that in Cu-W80. With increasing electrode diameter, arc column expansion velocity and diameter increase gradually. Breaking capacity is increasing with larger contact diameter.

Keywords: vacuum arc, forced current zero, transverse magnetic field, breaking capacity, electrode diameter and material.

1. Introduction

Forced current zero (FCZ) is a common method used to interrupt DC currents. This method for DC interruption forces the current to zero by injecting a high-frequency current of opposite polarity [1]. An oscillating current is generated by the resonance of a precharged capacitor and an inductor, and by superimposing this oscillating current over the current in the main circuit, the current is forced to zero. Then the breaker in the main circuit can interrupt the DC current successfully [2]. Thus, the burning arc in the vacuum interrupter (VI) can be extinguished by the FCZ. The experimental analysis of this switching method has been studied frequently [3].

The VI technology with very fast recovery precesses after current zero enables high current interruption with large current gradients ($\mathrm{d}i/\mathrm{d}t$). Thus, it was considered to be suitable for DC current interruption [4]. A successful interruption is significantly influenced by the transient characteristics of the current-commutation process, such as the rates of current and voltage at zero-crossing ($|\mathrm{d}i/\mathrm{d}t|$ and $|\mathrm{d}v/\mathrm{d}t|$). To reduce the size and cost of the forced-commutation branch, a high frequency is usually selected for the commutation branch. However, this condition is unfavorable for the recovery of dielectric strength as well as for the interruption capability of the VI after current zero. Glinkowski mainly researched the impact of the current zero-crossing time $\mathrm{d}i/\mathrm{d}t$ of the arc breaking [5]. In case of high frequency interruption, reignition issues is becoming more likely. There are more publications on the high-frequency currents, which can lead to multiple reignition and interruptions because of the reduced dielectric strength of the vacuum gap, mostly as a result of the small contact gaps.

Electrode and material are important fields in vacuum arc research. Niwa [6] and Sugita [7] investigated the effect of various contact materials on interruption phenomena by measuring the temperature of the anode surface. Liu [8] found the interruption capacity of vacuum interrupters with the slot-type AMF electrodes is related to the ratio of the anode diameter to the gap length. Lindmayer focused on the contact material for high-frequency vacuum arc experimental phenomenon [9]. In [10], properties of intermediate-frequency vacuum arc Influenced by electrode diameter and material in axial magnetic field were researched.

In this paper, the application of forced current zero method to DC circuit breakers for aviation 270 V power system was investigated. Experiments of different currents lower than 5 kA were carried out in interrupters with contact electrode materials being Cu-W80 alloy and Cu-Cr50 alloy at different forced commutation frequency. Besides, the breaking performances were also analysed with the diameters being 30 mm, 40 mm and 50 mm respectively.

2. Experimental setup

Four different commercial VI with spiral-type TMF electrodes without shield are used in this paper. The structural parameters are listed in Table 1. The air pressure inside the VI is 5×10^{-5} Pa. In order to reduce the contact resistance on the condition of ensuring

Contact type	A	B	C	D
Diameter	40 mm	40 mm	30 mm	50 mm
Contact material	CuCr25	CuCr25	CuCr25	CuCr25
Arcing material	CuW80	CuCr50	CuCr50	CuCr50
Contact resistance	12 µΩ	13 µΩ	17 µΩ	12 µΩ

Table 1. Structural parameters of electrodes in VI.

C_1 (µF)	L_1 (µH)	R_1 (mΩ)	f (kHz)
1620	3.4	22	2.1
1080	0.95	14	4.8
250	0.95	14	10.3

Table 2. Parameters of forced commutation branch.

breaking performance, the materials of contact surface and arcing surface are chosen differently. The arcing surface is weld to the base of electrode. When the contact material is Cu-Cr25, the contact resistance is between 12 µΩ to 17 µΩ. The arcing material of electrodes are Cu-W80 alloy and Cu-Cr50 alloy in type A and type B respectively. The contact gap is between 2–2.5 mm.

A direct circuit system is used to study the DC forced commutation interruption, as shown in Figure 1. The instantaneous short-circuit current is supplied from the capacitor C_0 with a capacitance value of 2 F, by triggering the bidirectional thyristor VT_0 controlled by the measure and control system. The main current ratings are obtained by adjusting R_0 which is varied from 55 mΩ to 500 mΩ. As the contact separation time is uncertain, the time of arc ignition is also uncertain; thus, an ignition circuit branch is designed to ignite the arc before the main current is injected. When contact separation occurs, an arc is formed between the anode and the cathode in the VI. At this time, the VI current is small as long as the arc could be maintained, until the contacts are fully open. This current is provided by VT_2, C_2, and R_2. The branch of R_3 and C_3 is designed as a frequency modulation circuit. The forced commutation branch includes VT_1, C_1, and R_1. The different forced commutation frequencies (2.1 kHz–10.3 kHz) are obtained by changing the parameters of forced commutation branch as are shown in Table 2. The varistors are used to absorb the energy stored in inductance when the circuit is interrupted.

The arc current is measured using a Rogowski Coil. A Phantom v7.3 high-speed video camera and a PC are used to record the arc appearances and the arc moving processes with a camera sampling rate of 72000 frames/s and exposure time of 1 µs. The parameters of the experimental system for DC forced interruption are listed in Table 3.

C_0	L_0	C_2	R_2	C_3	R_3
2 F	14 µH	50 mF	2.5 Ω	0.1 µF	0.1 Ω

Table 3. Experimental system parameters for DC forced interruption.

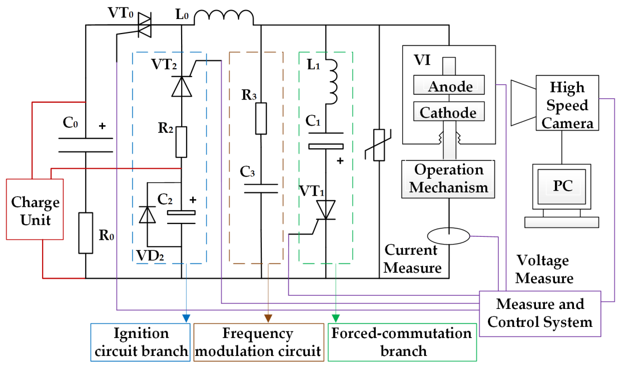

Figure 1. Experimental system for DC forced commutation interruption.

3. Results and analysis

3.1. Interruption characteristics

Waveforms of arc voltage for vacuum interrupters at about 3.3 kA with the same diameter (40 mm) but various forced commutation frequency are shown in Figure 2. The precharged voltages of commutating capacitor in forced commutation branch are 250 V, 224 V and 406 V, corresponding to 2.1 kHz, 4.8 kHz and 10.3 kHz. The waveform of arc voltage at 2.1 kHz is obtained with the branch of varistor, unlike the other two waveforms.

In order to increase the forced commutation frequency, the values of inductance and capacitance in the forced commutation branch need to be reduced. The low frequency is increased by reduction of the commutating capacitor. Thus, the voltage recovery time and interruption time is shorten. However, the over-voltage is much higher with high forced commutation frequency when the current is fixed. Besides, the varistor branch is set to absorb the energy. In order to reduce the over peak voltage, the capacitance in frequency modulation circuit should be larger. When the interruption current is about 3.3 kA, the negative voltages are –195 V, –110 V and –295 V with the increasing of commutation frequency. Comparing the peak of negative voltage in the different tests, it seems that

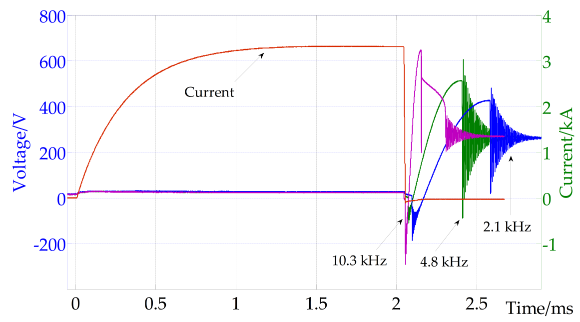

Figure 2. Waveforms of arc voltage for vacuum interrupters. (interruption current is about 3.3 kA, electrode diameter is 40 mm, the arcing time is 2 ms, the forced commutation frequencies are 2.1 kHz, 4.8 kHz and 10.3 kHz)

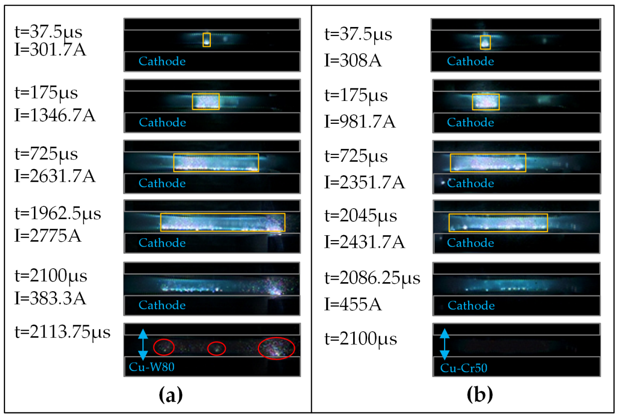

Figure 3. Typical vacuum arc appearance in (a) type A and (b) type B TMF contacts with 2 ms arcing time.

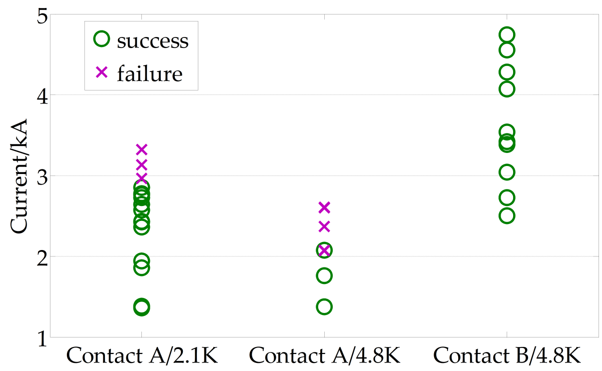

Figure 4. Interruption results of type A and type B vacuum interrupters with 2 ms arcing times at different forced commutation frequencies.

the peak value is related to the value of precharged voltage in forced commutation branch. The higher precharged voltage, the larger the negative peak value is.

3.2. Properties of vacuum arc influenced by electrode materials

Utilizing the experimental system described above, interruption experiments were carried out with currents of approximately 5 kA, using the type A and type B spiral-type TMF contacts. The typical vacuum arc appearance is shown in Figure 3 for 2 ms arcing time. The arcing materials are Cu-W80 (Figure 3 (a)) and Cu-Cr50 (Figure 3 (b)).

In both two types of contacts, at t=37.5 µs, a constricted arc developed and the arc in the contact anchored at the ignited point. At this early expansion stage, there were few or no cathode spots outside the central column. Then the cathode spots began to move around the arc column. The arcs moved, increasing the cross-sectional area and new cathode spots were formed constantly, which moved to the edges of the contacts. By the time t=2 ms with type A contact, the cathode spots had occupied almost the entire cathode surface, and they did not expand further. The cathode spots in the diffuse vacuum arc was also discussed in [11], and the TMF contact behaved as butt contact at the distance less than 3 mm. When the arcing time was 2063.9 µs, forced commutation was triggered, and the arc current began to decrease, flowing into the forced-commutation branch. With the decreasing of the arc current, the brightness of the arc and particles were reduced, and the metal vapour began to diffuse between the contacts. It was obvious that large amounts of metal vapour particles were filled the contact gap with the Cu-W80 contact.

The melting point and boiling point of W were much higher than that of Cr, which made the contact temperature higher for thermionic emission. The contact may be heated locally by arc under high current. For the locally high temperature, the electrons would be emitted intensively by the cathode and more metal vapours were generated and filled the gap, which was red circle marked in Figure 3 (a). With the increasing the particles, the probability of reignition increased after the current zero. The particle density grew rapidly and the conductivity of arc area was very good when the arc filled the contact gap, which caused a failure to interrupt at first current zero.

Interruption results and breaking capacity of type A and type B vacuum interrupters were shown in Figure 4 with 2 ms arcing times at different forced commutation frequencies. when the current was 2.1 kA and forced commutation frequency was 4.8 kHz the reignition occurred at first current zero, while under the same condition the breaking capacity was larger than 5 kA in Cu-Cr50 contact. Meanwhile, with increase of the forced commutation frequency, the breaking capacity was much lower in Cu-W80 contact.

3.3. Breaking performance with different electrode diameters

In order to analyse the influence of electrode diameters on the breaking capacity, experiments were conducted with type B, type C, and type D contacts for arcing times of 2 ms and 2.3 mm gap length. The forced commutation frequency is 10.3 kHz. The experimental results of the breaking performance are shown in

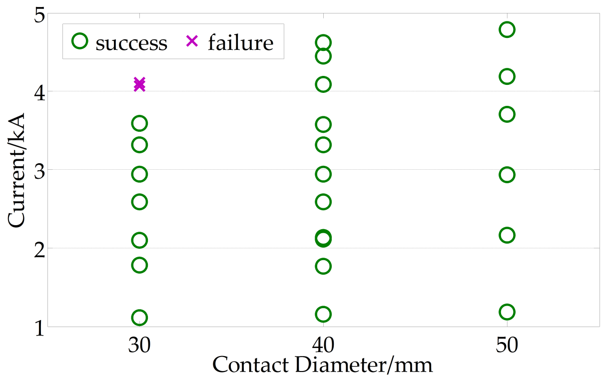

Figure 5. Breaking experiment results of different electrode diameters with 2 ms arcing times at 10.3 kHz forced commutation frequencies.

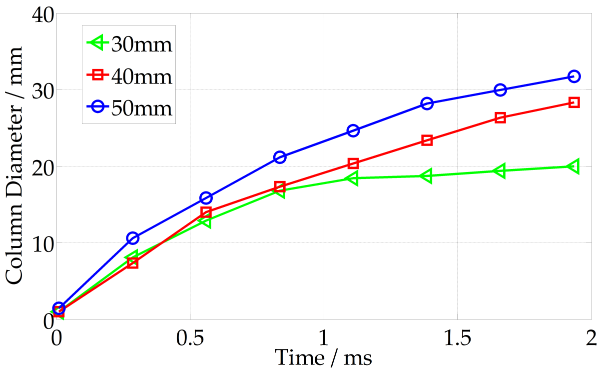

Figure 6. Diameters of diffuse columns at 3.3 kA with different electrode diameters.

Figure 5.

It can be concluded that, as the electrode diameter increases, the breaking capacity of VI is greatly improved. When the electrode diameter is 30 mm, the reignition at first current zero occurs, and the maximum breaking ability is about 4 kA. The diameters of the diffuse columns at 3.3 kA with different electrode diameters are shown in Figure 6. In the early stages of column diffusion, the arc expands rapidly. The larger the electrode diameter, the faster the expansion will be. With increase in the diffusion diameter, the arc diffusion velocity will decrease gradually. After approximately 1.4 ms, the arc tends to expand slowly. The maximum column diameter is proportional to the electrode diameter.

4. Conclusions

Based on method of FCZ, the properties and breaking performances of spiral-type TMF contacts were investigated for 270 V DC application and the results were summarized below:

The negative peak voltage is not only determined by the commutation frequency but also related to the value of precharged voltage in forced commutation branch. The higher precharged voltage, the larger the negative peak value is.

For the locally high temperature, the electrons are emitted intensively by the cathode and more metal vapours are generated and filled the gap in the Cu-W80 contact. Thus, the breaking capacity in Cu-W80 electrode is much lower than that in Cu-Cr50 electrode. With increase of the forced commutation frequency, the breaking capacity is much lower in Cu-W80 contact.

The larger the electrode diameter, the higher speed and the lager maximum column diameter of the expansion will be. As the electrode diameter increased, the breaking capacity of VI is improved.

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