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High-current Interruption in Vacuum Circuit Breakers

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ABSTRACT

The aim of this project was to find a correlation between contact gap length and switching behavior of a vacuum circuit breaker. A large number of interruption experiments was executed in a vacuum chamber with butt type contacts made of Cu, CuCr 50/50 and AgWC. The currents to be interrupted varied from 2.5 to 32 kA. The rate of change of current and recovery voltage were kept at a fixed value at current zero. Many re-ignitions of the dielectric type, scattered over a wide range of re-ignition voltages, were observed and only a few of the thermal type. The total amount of energy dissipated in the vacuum chamber appears to be determinative for the type of re-ignition. On Cu severe anode spot melting was found, whereas CuCr and AgWC suffered little anode melting. The wide range of re-ignition voltage values found shows that a straight correlation with the contact gap length can not be defined. At 5 to 10 μs after current zero a 'second' post arc current did appear.

1. INTRODUCTION

FOR design and manufacturing it is important to know the current interruption performance of the VCB (vacuum circuit breaker) under different conditions, e.g. arc current, arcing time, gap length. After current zero the TRV (transient recovery voltage) appears over the opened contacts and can cause a re-ignition. Whether this happens or not depends on many parameters like: di/dt just before current zero, du/dt just after current zero, contact distance d at current zero, peak value of the arc current, arcing time, contact material, and the shape of the contacts.

Especially the interruption performance of short circuit currents, in the range of 10 kA is of interest. In this case current constriction and anode spot formation can occur easily [1-4]. When anode spot melting has occured the re-ignition will be of the thermal type due to the abundance of particles in the contact gap [1, 2]. At low currents the recovery of dielectric strength depends, apart from the used contact material, on the rate of rise of current and voltage and on the gap length at current zero [5]. The experiments were performed with the following contact materials: Cu, CuCr 50/50 and AgWC (Toshiba Co.). The contacts used were of the butt type, so no axial magnetic field was induced. During the experiments the rates of rise of current and voltage were kept constant, thus for a specific experiment only the gap length, the peak value of the arc current and the arcing time varied.

2. EXPERIMENTS

2.1. TEST CIRCUIT

The experiments were executed with the well known Weil-Dobke synthetic circuit, shown in Figure 1. It consists of a main current circuit, containing a capacitor bank C (890 μF), transformer T ($L_{tr} = 21.5$ mH, $R_{tr} = 1.49\Omega$) with $f_{main} = 36.4$ Hz; a current injection circuit, containing: a capacitor Cr (27.8 μF), coil L (1.27 mH), and air gap switch SG, with $f_{inj} = 847$ Hz, $\widehat{i}_{inj} = 2.2$ kA and $(di_{inj}/dt)_{cz} = 11.7$ A/μs; a TRV circuit containing capacitor C_{TRV} (20 nF) and coil L_d (32 μH), with $f_{TRV} = 32$ kHz, $\widehat{u}_{TRV} = 25$ kV and $du_{TRV}/dt = 1.9$ kV/μs.

The test object is VCB-I, a demountable vacuum chamber equipped with butt type contacts of the different materials, all with a diameter of 25 mm. VCB-II is a back up switch to prevent the TRV from entering the low voltage components of the main circuit. During the first half cycle of the main current, VCB-I and VCB-II are opened simultaneously, where VCB-II interrupts at main current zero, whereas VCB-I is still conducting the injection current which was triggered 0.3 ms before current zero. After current zero of the injection circuit the TRV only acts on VCB-I.

Figure 2 shows the full performance of a test run: (a) main and injection current; (b) arc voltage; (c) arc light intensity and (d) gap length. The initial contact opening speed is 1.8 m/s and the average speed until
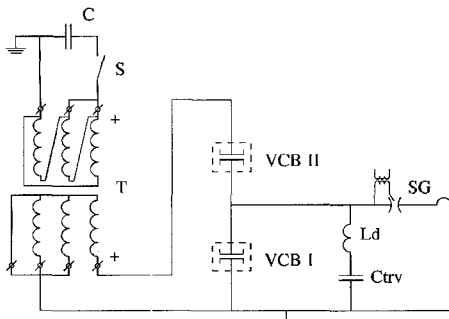
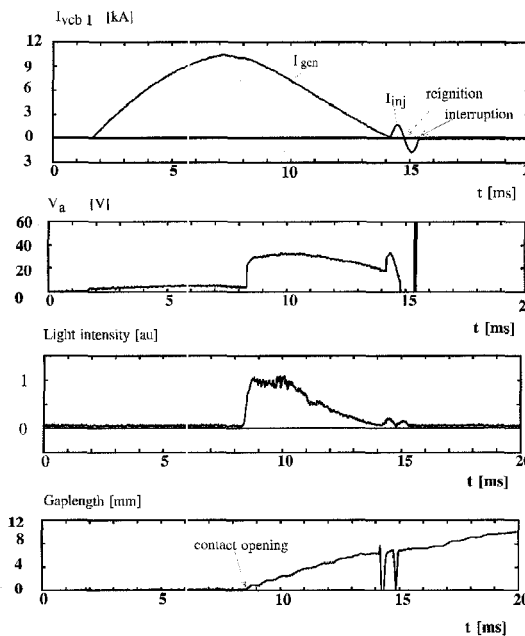Figure 1. Main components of the Weil-Dobke synthetic circuit.

Figure 2. A typical example of a measurement with the Weil-Dobke synthetic circuit.

the cathode has reached its end position is 1 m/s. Because the contact opening speed could not be adjusted, it was not possible to set independently the arcing time and contact gap at current zero.

2.2. EXPERIMENTAL RESULTS

In order to obtain information about the relationship between re-ignition occurrence and actual re-ignition voltage U_r on the one hand and maximum arc current $\widehat{i}_a \leqslant \widehat{i}_{gen}$, dissipated arc energy $\int i_a u_a dt$ and contact gap length d on the other hand, a large series of experiments was executed with the three different materials. During these experiments di/dt and dU_{TRV}/dt were kept constant at the aforementioned values. Around current zero detailed measurements of U_{TRV} and i_a were made at high time resolution as shown in Figure 3 [6, 7].

In Figure 3(b) we see from $t = 2.5$ μs the injection current declining with a rate of 10.1 A/μs and passing current zero at $t \approx 5$ μs. The post arc current has a maximum of ~1 A at $t = 5.5$ μs. Meanwhile the TRV appears (Figure 3(a)) with a rate of $dU_{TRV}/dt = 1.6$ kV/μs. At $t = 14.5$ μs re-ignition takes place at a TRV value of -13 kV. From this high value it is clear that a dielectric re-ignition occurs. Only in a few cases, especially with AgWC-contacts, thermal re-ignitions ($U_r \leqslant$
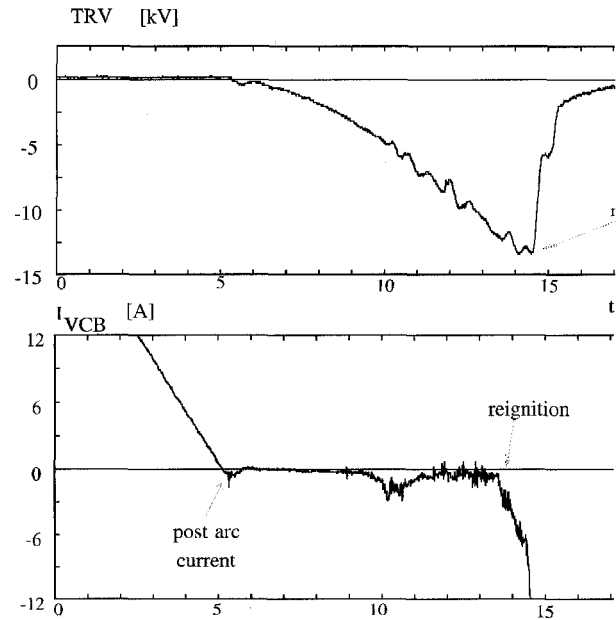

Figure 3. A typical example of fast measurements around current zero: TRV across VCB-I (a); current through the tested VCB-I (b).

1 kV) were observed. On both current and voltage curves instabilities can be seen which will be discussed in Section 2. They were observed in many experiments but do not always lead to a re-ignition.

For copper contacts some calculations and experiments were made in order to determine whether arc constriction and anode spot formation will take place at high current interruption or not [1, 2, 8, 9]. The calculations are based on the method described by Rich [10] and Jolly [11] where the power density balance at the anode surface is considered. The energy input from the arc into the anode and the energy loss from the anode are determined, so the anode temperature can be found from the heat conduction theory. Essential is at what time after contact separation the anode surface temperature exceeds the copper melting temperature $T_{mCu} = 1092°C$. The computational results are compared with the arc voltage and the light intensity measurements from the arc region, made by means of an optic fiber and photo-diode. The measurements are shown in Figure 4 for different values of the main current and ~12 ms of arcing time, which covers most of the main current half period of 16 ms. With increasing main current, a strong increase in light intensity is measured whereas the arc voltage shows a slight increase and occurrence of unstable behavior. Although the calculations predict that for case A with $\widehat{i} = 4.1$ kA, the anode temperature will exceed the copper melting temperature for a short period of time, the measurements (Figure 4(a)) show no effect on the arc voltage peaks or the increase in light intensity. Therefore, in this case current contraction or anode footpoint formation is not expected to happen. For case B with $\widehat{i} = 6.7$ kA, the calculations predict the anode temperature to exceed the copper melting temperature at $t = 4.3$ ms where the measurements show an increase of arc voltage instabilities at 4.5 ms. For case C, $\widehat{i} = 10.4$ kA, the prediction of the anode temperature to exceed T_{mCu} is at 3.7 ms where both the arc voltage and light intensity measurements show an increase at 3.8 ms. These results, together with the strong increase in light intensity from case B (6.7 kA) to case C (10.4 kA)

and the sudden jump in light intensity at 3.8 ms for case C lead to the conclusion that current constriction takes place, and that in case C anode spot formation is very likely.
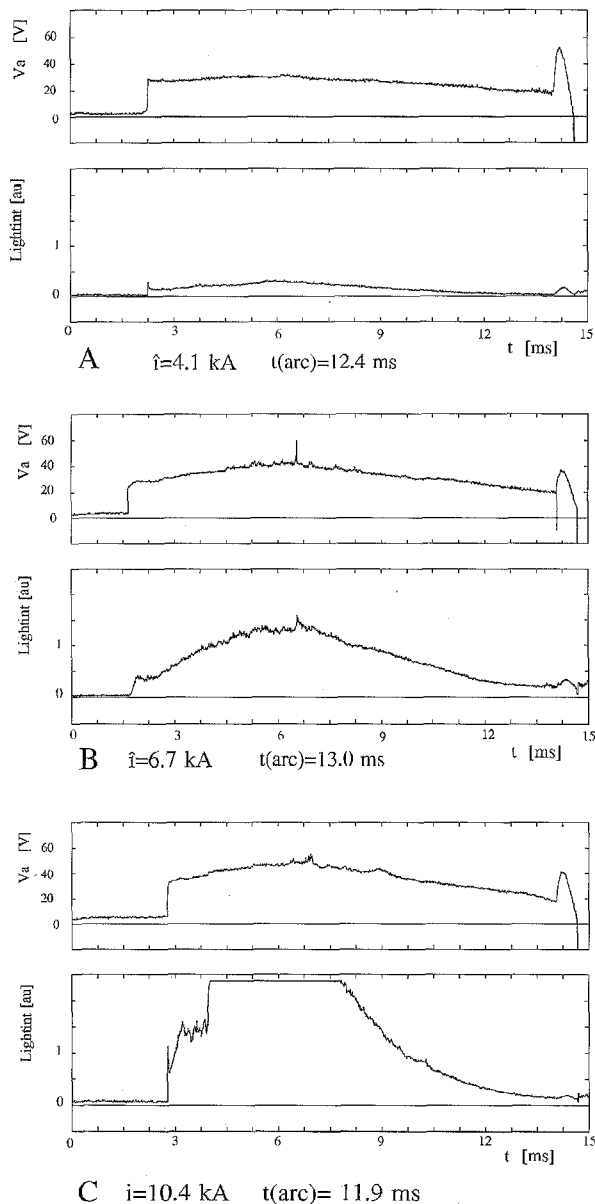

A　　î=4.1 kA　　t(arc)=12.4 ms

B　　î=6.7 kA　　t(arc)=13.0 ms

C　　i=10.4 kA　　t(arc)= 11.9 ms

Figure 4. Measurements of arcing voltages (upper traces) and light intensities (lower traces) for three peak currents, on copper contacts. Arcing time is kept at ~12 ms. At 10.4 kA arc constriction is evident. (a) $\hat{i} = 4.1$ kA, (b) $\hat{i} = 6.7$ kA, (c) $\hat{i} = 10.4$ kA.

Furthermore, the contact erosion rate has been determined by measuring the electrode masses before and after the interruption measurements. The average erosion rate is calculated by dividing the total electrode mass loss by the total arcing charge that was transferred in the particular measurements series. The results are compiled in Table 1.

From the Table it is clear that AgWC has the lowest erosion rate and Cu the highest, whereas the Cu-anode has lost much material and the

Table 1. Erosion rates of anode "a" and cathode "c" for contact materials Cu, CuCr 50/50 and AgWC.

contacts		init mass g	final mass g	total charge C	erosion rate μg/C
Cu	a	205.2502	204.1365	1310	850
	c	202.8224	202.5963	1310	173
Cu/Cr 50/50	a	204.2810	204.2739	2000	3.6
	c	202.5862	202.2660	2000	160
AgWC	a	202.9404	202.8865	2130	25
	c	200.5396	200.5247	2130	7.0

CuCr-anode only a small amount. This is also an indication for the occurrence of anode spots. A visual inspection confirmed the existence of intense arc spots on the Cu anode whereas the CuCr and AgWC anodes showed less evidence of severe anode melting.

3. DISCUSSION

3.1. INTERRUPTION PERFORMANCE

Under the conditions, established in the experimental setup, many interruptions led to re-ignition for all three contact materials. The interrupted main current ranges from 2.5 to 32 kA. Figure 5 shows the compiled data of re-ignition voltage U_r and maximum main current for different regions of gap length and the contact materials Cu, CuCr 50/50 and AgWC, respectively.
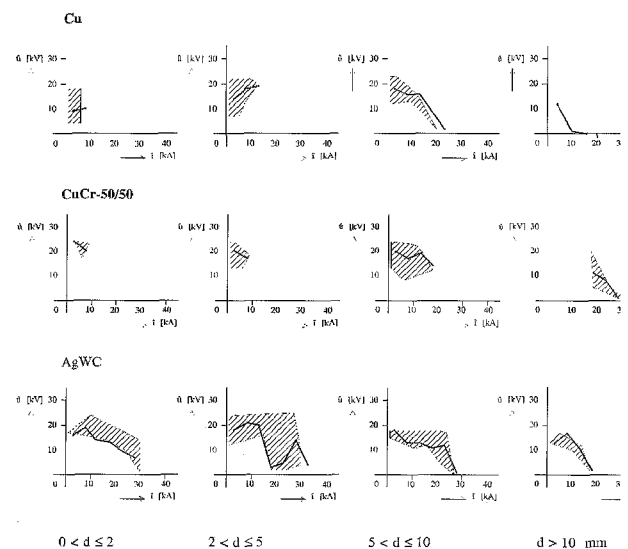

Figure 5. Envelope drawing of measured re-ignition voltages as a function of main current peak for each gap length group. The solid lines connect the mean re-ignition voltages in the particular current ranges.

The original datapoints $(\hat{i}, \hat{u}(= U_r))$ are compiled in groups in the hatched areas for four different gap length regions. From this we notice that for gap lengths $d \leqslant 5$ mm Cu and CuCr contacts merely have dielectric restrikes, indicated by the high value of the restrike voltage, $\hat{u} > 4$ kV. Within these regions of gap length the AgWC contacts show at high peak main currents, $\hat{i} > 18$ kA, already occasionally thermal re-ignition, $\hat{u} \leqslant 1$ kV. In the gap lenth region $5 < d \leqslant 10$ mm the

CuCr contacts show their superior behavior: they do not exhibit thermal re-ignition whereas both Cu and AgWC contacts do. Finally in the region of fully opened contact gap, $d > 10$ mm, where all arc currents pass through the main current maximum, the Cu contacts show thermal re-ignitions for $\hat{i} > 10$ kA, AgWC contacts for $\hat{i} > 15$ kA and CuCr contacts prove their superiority having thermal re-ignition only for $\hat{i} > 20$ kA. The thermal type re-ignitions for gap lenghts $d > 5$ mm and $\hat{i} > 10$ kA are also an indication of the existence of anode spots.

In the region $d > 10$ mm two features act together: the high peak value of the main current and the long arcing time (coinciding with the large gap length). Here the total energy dissipated in the arc W_a will result in a high concentration of cathode material in the gap and eventually when current constriction takes place and anode spots are formed, much anode material will added to the metal vapor plasma in the contact gap. In that case ionized material will stay in the inter electrode gap for ~5 μs and can cause a thermal re-ignition [9]. For all three electrode materials used this has happened several times. An indication for the high plasma density [8] in these cases is given by the long pumping time necessary to bring the vacuum chamber back to working conditions, pressure $p \leqslant 10^{-5}$ Pa.
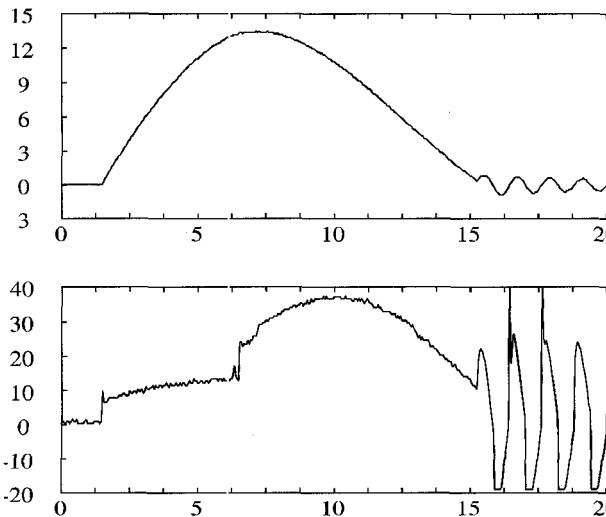

Figure 6. Specific interruption performance of AgWC contacts. (a) Main current and injection current with multiple re-ignitions;(b) arc voltage, suggesting thermal re-ignitions.

Figure 6 is a good example of the specific performance of the AgWC electrodes. It is known that this contact material is especially useful for low surge circuit breakers. Figure 6(a) shows the first half cycle of the main current followed by the injection current which suffers from 9 re-ignitions, from which numbers 6 and 8 are surely thermal re-ignitions. This follows from the low value of the arc voltage Va that does not exceed 40 V. The many re-ignitions observed with the AgWC contacts make it clear that they are not suited for high short circuit current interruption.

The influence of the dissipated arc energy on the re-ignition performance is best shown in Figures 7, 8, and 9 where the averaged electric field strength $E_r = U_r/d$ is exhibited as a function of the dissipated arc
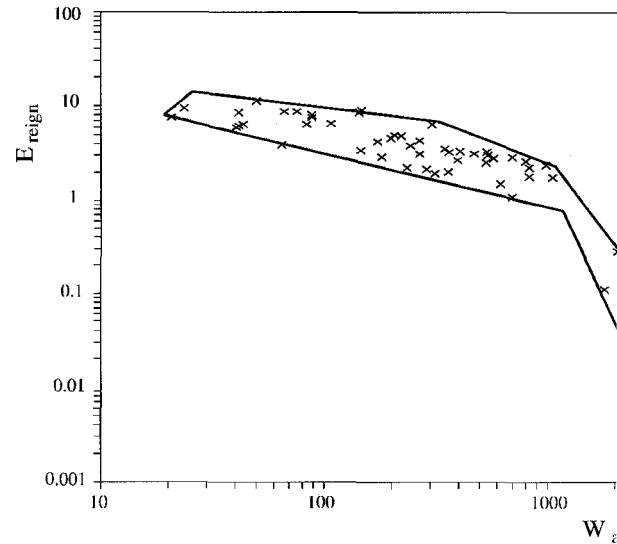

Figure 7. Re-Ignition electric field strength as a function of arc energy for Cu contacts.
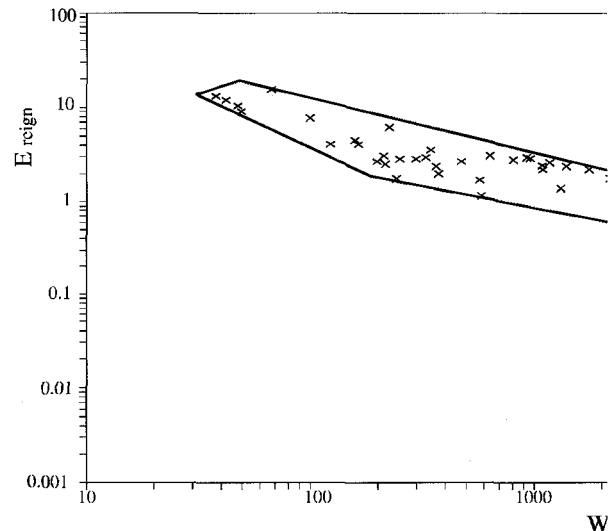

Figure 8. Re-Ignition electric field strength as a function of arc energy for CuCr 50/50 contacts.

energy

$$W_a = \int_{t_a} u_a(t) i_a(t)\, dt \tag{1}$$

The collection of rather stochastically scattered data points in Figures 7 to 9 indicate that more features are involved than the ones mentioned in the introduction. After each interruption the surface conditions of both cathode and anode will be changed. On the cathode new craters will be formed and the anode may have new melting spots. It is known that these surface irregularities have a strong influence on the local electric field strength which in many cases plays an important role in the re-ignition process. Nevertheless the enveloping curves clearly show a tendency of declining electrical field strength E_r with increasing arc energy W_a. For all three contact materials we see a sudden sharp drop in the re-ignition field strength above a certain critical value of W_a, see Table 2.
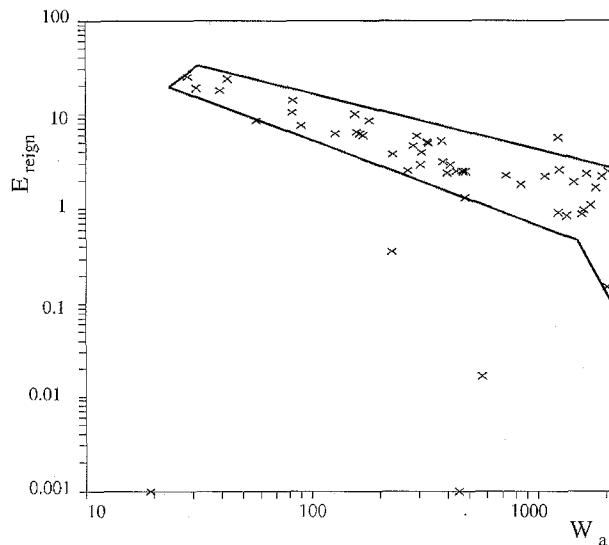
Figure 9. Re-Ignition electric field strength as a function of arc energy for AgWC contacts.

Table 2. Critical dissipated arc energy W_a for the contact materials Cu, CuCr 50/50 and AgWC.

contacts	crit.W_a J
Cu	1000
Cu/Cr 50/50	3000
AgWC	2000

3.2. SECOND POST ARC CURRENT

In Figure 3 we have seen the appearance of a 'second' post arc current i_s at $t \sim 10$ µs. From the many experiments it was clear that this current peak coincides with the maximum of du_{TRV}/dt and is mainly capacitive with a small resistive part. The stray capacitance of VCB-I and the plasma resistance are supposed to be the origin of this current is. The same phenomena were found with a TRV-frequency of 60 kHz where the second post arc current appeared at $t = 5$ µs. The high frequency disturbances on U_{TRV} are due to the circuit C_{TRV}/L_d/VCB-I. When the plasma resistance is low enough, re-ignition can set on as is demonstrated in Figure 3.

4. CONCLUSIONS

FROM the large amount of experimental data collected during this project several conclusions about the performance of the investigated contact materials can be drawn.

First of all it is shown that with simple diagnostic means such as the measurement of arc voltage, arc current, contact movement and light intensity, the interruption performance can be fruitfully investigated.

At small gap length and peak main currents < 25 kA all contacts materials used (Cu, CuCr, AgWC), showed high re-ignition voltages (> 4 kV) indicating dielectric re-ignition. Only AgWC contacts showed a tendency for lower re-ignition voltages at higher currents.

At large gap length, coinciding with long arcing times, a tendency is found for lower re-ignition voltages, occasionally $U_r < 1$ kV, indicating thermal re-ignition.

The re-ignition electrical field strength declines with the dissipated arc energy W_a and at a certain critical value of the arc energy W_a between 1000 and 3000 J, depending on the contact material, a sudden drop of re-ignition electrical field strength by a factor of 10 was observed.

From the three materials, Cu showed the highest erosion rate, especially at the anode, and AgWC the lowest. The material loss of the CuCr anode was lowest indicating that it is the best choice of the three for short circuit interruption.

The experiments confirmed the capability of AgWC as a low surge material demonstrated by the frequent re-ignitions at low re-ignition voltages.

Evidence of severe anode spot melting was observed on Cu contacts only, whereas CuCr and AgWC contacts showed traces of slight anode surface melting.

The stochastic behavior of the re-ignition voltages did not show a straight correlation between contact gap length and re-ignition voltage.

A second post arc current was found, originating from the stray capaintance of the VCB and the plasma resistance, which in many cases initiated the re-ignition.

ACKNOWLEDGMENT

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