Gap-length dependent phenomena of high-frequency vacuum arcs

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Gap-length Dependent Phenomena of High-frequency Vacuum Arcs

by
H.Q. Li
R.P.P. Smeets

EUT Report 93-E-280
ISBN 90-6144-280-X

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Subject headings: vacuum switchgear / circuit-breaking arcs / high-frequency discharges.
Abstract

This report shows the results of a study dealing with the interruption of high-frequency current (few hundred kHz, few hundred A) by vacuum interrupters, used in power distribution systems.

With a special 40 kV circuit, phenomena around current zero of the HF arc were investigated in detail. Special attention was paid to the effect of vacuum gaplength (fixed in the range 0.1 - 1 mm), circuit (realised with discrete LC components) and contact material (Cu, CuCr and AgWC).

It was found that interruption of HF currents is mainly determined by the ability of the HF circuit to provide sufficient voltage after HF current zero to breakdown the short vacuum gap. Thus, the interruption ability is primarily depending on the momentary breakdown voltage of the gap which is a function of gaplength, contact material and arcing history. A crucial role is played by the very fast transient recovery voltage (few 100 kV/μs) that is produced by parasitic components in the immediate vicinity of the interrupter in power distribution networks.

Keywords: vacuum switchgear, circuit-breaking arcs, high-frequency discharges, high-voltage engineering.

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EUT Report 93-E-280

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1. INTRODUCTION

When a vacuum switch is used to switch an inductive circuit a transient phenomenon called multiple reignition may occur. This multiple reignition can cause voltage escalation and, especially in the three-phase circuit case, another phenomenon called virtual current chopping. Attention had already been paid to these phenomena in early 1970's [1, 2] because the overvoltage caused by the phenomena is hazardous. It is found that the surges caused by such phenomena may endanger the turn-to-turn insulation of the load such as motors and transformers, even if the crest value of the surges is not so high.

In application there have been some times accidents which are believed to be caused by the above phenomena because the current chopping level is quite low in the case. So the two factors being responsible for the mentioned surges, circuit parameters and the behaviour of high frequency (HF) arc, are constantly the subject of those who are interested in the phenomena.

Analytical and simulation methods are used to consider the effect of the parameters of the different circuits on the overvoltage resulting from the HF arcing [1, 2, 3]. Meanwhile experimental and theoretical methods are used to understand the phenomena and behaviour of HF vacuum arc. M. Lindmayer and E.-D. Wilkening measured the effects of circuit parameters on the reignition voltage distribution of short vacuum gaps (mostly gap length being 64 μm) of different contact materials [4] and deduced that at higher currents, where low reignition voltages dominate, the reignitions occur in the old arc channel, favoured by the strong field of the space charge sheath in front of the new cathode [5]. Z. Zalucki [6, 7] measured the phenomena of HF vacuum arc at a gap length of 0.3 mm and also estimated that if high frequency arcs developed from one point there are high concentrations of cathode spots and high power densities on the anode. He also concluded that the large dispersion of reignition voltages results from the random distribution of cathode spots, changeability of microrelief on the electrode surface, and different local cathode erosion rates in successive discharges. All the research shows that for a certain set of conditions, such as circuit parameters and certain contact materials, the reignition voltages observe a certain distribution.

Apart from the understanding of the physical background of HF vacuum arc, the aims of the measurement of HF arcing phenomena of most researchers are to give a practical criterion of HF current interruption, which can be applied to analytical or statistical simulating methods to estimate the overvoltage in practical circuits. In practical situations the multiple reignitions and virtual current chopping occur when the gap length of the reignition pole of the switch is still small (less than 1 mm). Though the gap length is quite small, it is continuously increasing due to the opening of the contacts. So the method using the data measured from one fixed gap length or opening gap length to estimate the overvoltage may be sensitive to the specific conditions because for the one-fixed-gap measurement it is not clear if the data also fit other gap length and for the opening-gap measurement the opening speed of the
considered switches will have to be comparable or the moving characteristics of the contacts should be similar.

In the former work of this research group in the Eindhoven University of Technology a HF current interrupting model is obtained, which comprises a dielectrically dominated current interrupting criterion and a thermally dominated current interrupting criterion [8]. The dielectrically dominated interrupting criterion can be expressed as

$$ U_m < U_o \cdot \alpha_0 $$

where $U_m$ is the peak value of ultra high frequency (UHF) recovery voltage after each current zero, $U_o$ the momentary cold breakdown voltage and $\alpha_0$ the voltage reduction factor. It is found that $\alpha_0$ is nearly a constant for one kind of contact material. The conception of $\alpha_0$ is that the breakdown voltage of one vacuum gap without arcing (cold breakdown voltage $U_o$ ) and just after HF arcing (reignition voltage $U_i$) are different and the relation between them can be described by this factor ($\alpha_0 = U_i/U_o$).

From the view point of this criterion the interruption of a HF current only depends on the question if the decaying $U_m$ is smaller than a certain value of $U_o \cdot \alpha_0$.

The thermally dominated criterion can be expressed as

$$ U_m < U_o \cdot \alpha(i_m), $$

with $\alpha(i_m) = 0$ if $i_m >$ a certain threshold current (thermally)

$= \alpha_0$ if $i_m <$ a certain threshold current (dielectrically)

where $\alpha(i_m)$ is a current dependent voltage reduction factor.

The model has been supported by measurement for Cu, CuCr, CuW, CuTeSe, CuBi and AgWC contact materials [9]. In the measurement the capacitor in the HF circuit is being charged while the gap length is increasing. At the instant when the voltage of the capacitor is higher than the momentary voltage withstanding ability of the opening gap the gap breakdown and the HF arcing begins. The maximum value of HF current is proportional to the voltage of the capacitor at the instant of breakdown ($C$ and $L$ are constants in a specific HF circuit) and therefore to the momentary breakdown voltage of the gap. This is the same situation as in a practical case. But in practical circuits, $C$, $L$ of the HF circuit, UHF recovery characteristics after HF arcing and opening speed may be different from the investigated case and so there may be some difference between the real overvoltage and the calculated one from the model. It is nescissery to know if the HF current interrupting phanomenon is circuit dependent.

The aim of this research is to obtain a conception if the gap length has some effects on HF arcing phenomena and to give a further support to the HF current interrupting criterion mentioned above from another view point.

When current is larger than a critical value (e.g. 72A for AgWC contact material [9]) from which the thermally dominated interrupting criterion applies the interrupting ability is rather a random phenomena, so the attention is mainly paid to dielectrically dominated interrupting phenomena in this research.
2. EXPERIMENTAL SET-UP

As mentioned above, the aim of this research is to get information how the gap length affects the HF vacuum arc and to give further support to the interrupting model. In order to compare the results of measurement at different gap length, the test circuit must insure as equivalent as possible the conditions near current zero at different gap length. From the results of former research, it is known that under the same other conditions the rate of change of the current at current zero has decisive effects on the dielectric recovery process. So a circuit which can produce the same $\frac{di}{dt}$ for the same value of residual voltage of capacitor C (the frequency and amplitude of the current may change) is used in the measurement.

2.1 TEST CIRCUIT

The experimental circuit for fixed gap HF arcing phenomena measurement is shown in Fig.1. High voltage transformer T, resistor R, (2.5MΩ), rectifier D and capacitor C, (0.97µF) form a high voltage DC power source which supplies the high voltage to the HF circuit. The output voltage of the DC power source can be changed by adjusting the primary input voltage of the high voltage transformer. Capacitor C, inductor L and the vacuum interrupter VI constitute the high frequency (HF) circuit which supplies the HF current to HF arcing. $C_o$ is a changeable capacitor (including the parasitic

![Experimental circuit for HF arcing phenomena measurement with fixed gap length](image-url)
capacitance of the VI and the introduced capacitance by the voltage divider), which, together with the inductor L, forms the ultra high frequency (UHF) circuit producing UHF recovery voltage over VI after each half-cycle of current of HF arcing. C and L determine the frequency of the HF current, while C₀ and L determine the frequency of UHF recovery voltage. Rₛ, a 4.8MΩ resistor, is used to continuously charge the capacitor C before measurement and disconnect the HF circuit from the DC power source during the measurement due to large time constant (Rₛ•C). Switch SW, a rotatable-bar air gap disconnecting switch, is used to start each shot (measurement). The circuit can work at high voltage (the rated voltage of the transformer T and capacitor C is 100kV (rms) AC and 150kV DC respectively). Without changing the main structure the circuit can be used for other purpose (e.g. cold recovery process of a vacuum switch).

The gap length of the vacuum interrupter can be measured by a transducer-strain-gauge system or a digital vernier calliper. The transducer-strain-gauge system can also be used to measure the dynamic gap length during the operation of the switch (readers are referred to [10]). The research described in this report only involves static or fixed gap length measurement.

The fixed gap HF arcing phenomena measuring process is as follows. First, fix the vacuum gap to a predetermined length and adjust the primary voltage of the transformer T to a certain value, so a required DC voltage will charge the capacitor C continuously through the resistor Rₛ. Then, SW is switched on and at the same time a UHF transient voltage is applied to the gap of the vacuum interrupter VI. This

![Fig.2 The waveform of the UHF transient over the vacuum interrupter](image)

transient voltage breaks down the vacuum gap of VI and initiates the HF vacuum
arcing. At last the waveform of current and voltage are recorded by a LECROY 9400 digital oscilloscope (sampling time 10ns) through a Pearson current transformer (20 A/V) and a self-made capacitive voltage divider (6.05 kV/V). The parameters of all the main instruments and components are given in APPENDIX A.

The prospective maximum value of current $i_m$ which the HF circuit can provide with different $C$, $L$ and initially charged voltage $U_c(0)$ is listed in Tab.1.

**Tab.1 prospective maximum current the circuit can provide**

<table>
<thead>
<tr>
<th>$C$ (nF)</th>
<th>$L$ (μH)</th>
<th>$U_c(0)$ (kV)</th>
<th>$i_m$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>41.4</td>
<td>45</td>
<td>990</td>
</tr>
<tr>
<td>20</td>
<td>147</td>
<td>40</td>
<td>467</td>
</tr>
<tr>
<td>10</td>
<td>147</td>
<td>45</td>
<td>371</td>
</tr>
<tr>
<td>10</td>
<td>147</td>
<td>40</td>
<td>330</td>
</tr>
<tr>
<td>6.6</td>
<td>147</td>
<td>45</td>
<td>302</td>
</tr>
<tr>
<td>6.6</td>
<td>147</td>
<td>40</td>
<td>268</td>
</tr>
<tr>
<td>3.3</td>
<td>147</td>
<td>45</td>
<td>213</td>
</tr>
<tr>
<td>3.3</td>
<td>147</td>
<td>40</td>
<td>190</td>
</tr>
<tr>
<td>3.3</td>
<td>147</td>
<td>20</td>
<td>95</td>
</tr>
</tbody>
</table>

The waveform of UHF transient voltage appearing over the vacuum interrupter is shown in Fig.2.

The advantage of such a circuit is that the capacitor $C$ can be pre-charged to a voltage at different fixed gap length. In theory, no matter what the cold (initial) breakdown voltage of the vacuum gap is the peak value of current of the first half-cycle is the same (for same $C$ and $L$). And as long as the residual voltage of capacitor is the same and the $L$ is the same the $\frac{di}{dt}$ before last current zero will also be the same. This is because in a $L$-$C$ oscillation circuit the $\frac{di}{dt}$ at current zero is determined by the voltage over $C$ and the inductance $L$ ($\frac{di}{dt}=\frac{U_c}{L}$).

**2.2 GAP LENGTH ADJUSTMENT AND MEASUREMENT**

As mentioned above there are two methods available in the experimental set-up to measure the gap length. In the measurement described in this report the gap length is measured by a digital MITUTOYO vernier calliper (the nominal accuracy of the calliper is 0.01 mm). The gap length is adjusted by a screw-nut system. The principle of the gap length adjustment is schematically shown in Fig.3. First, the contacts of the vacuum interrupter contact each other before adjustment. Therefore reset the display of the vernier calliper to zero. Now the reading of the ohm meter is zero. Further more,
Fig.3 The schematic diagram of gap length measuring system

rotate the nut and read the displayed data of the vernier calliper till the instant when the reading of the ohm meter suddenly changes from 0Ω to >0Ω. At last rotate the nut further to make the increment of the display of vernier calliper (the gap length) to the predetermined value.

2.3 VOLTAGE MEASUREMENT

The peak value of the voltage can be expected over 60 kV in the measurement of this research, so a capacitive voltage divider is made to meet the requirement. The structure of the voltage divider, including the high voltage and low voltage signal cables, is schematically shown in Fig.4. Two 50Ω characteristic resistors are used to damp the reflection of travelling waves. A 660Ω resistor is used to damp the oscillation between the voltage divider and high voltage signal cable. The value of this resistor is determined by trying a number of resistors and choosing the one with the best effect. The high voltage arm of the divider consists of 10 ceramic capacitors (500pF and 20kV each) in series. The low voltage arm of the divider comprises four paralleled 0.1 μF capacitors which, together with the characteristic resistor, form a coaxial structure.

When measurement is going on there is some electromagnetic radiation which makes the measurement rather difficult. The function of the high voltage signal cable is to keep the voltage divider a relatively large distance from the radiation source (HF circuit, UHF circuit and the gap of rotatable-bar air switch in this case) so the interference signal can be much attenuated. Attention should be paid to the fact that a long high voltage cable will introduce capacitance. So the length of the high voltage
Fig. 4 Schematic diagram of self-made voltage divider and voltage measuring system

cable should be proper (2.6m and a introduced capacitance of 250pF in this research). The copper screen case further shields the divider from the source of interference.

The self-made voltage divider is calibrated with a Tektronix P6051 probe by measuring the same signal. The attenuation ratio of the self-made voltage divider is 6050:1, and the rise time is approximately 50 ns (bandwidth: 7MHz).
3. DEFINITIONS AND RESULTS OF THE MEASUREMENT

In this report a reignition means one half-cycle of HF arcing and a reignition voltage the voltage which starts (by breakdown of the gap) the reignition. For convenience of discussion, similar to reference 11, four types of reignitions are defined for a shot as following:

Type 1: This reignition, the first in one shot, starts after the cold (initial) breakdown of the vacuum gap (this half-cycle of HF arcing is called "reignition" here because in real situation it occurs after 50Hz current arcing or last reignition).

Type 2: This reignition starts immediately after the previous reignition at an unperceptible reignition voltage (less than about 1kV).

Type 3: This reignition starts after the previous reignition but before the UHF transient recovery voltage reaches its first maximum at a perceptible breakdown voltage (higher than about 1 kV).

Type 4: This reignition starts after the UHF transient recovery voltage of the previous reignition reaches its maximum.

A typical waveform of current and voltage of one shot is shown in Fig.5. In the figure,

![A typical voltage and current waveform. Current (upper trace): 60A/div, voltage (lower trace): 6.05kV/div time: 5μs/div.](image-url)
to stands for the instant at which the switch SW is closed electrically (there is a prebreakdown of the air gap), \( t_1 \) the breakdown of the fixed gap of VI, \( t_2 \) the second reignition, \( t_3 \) the temporary interruption, \( t_4 \) the reignition of the gap and \( t_5 \) the final interruption of the HF arcing current (Fig.5 is measured from a vacuum interrupter with AgWC contact material and a gap length of 0.4mm).

For voltage, the peak value of the first voltage spike is called the cold breakdown or initial reignition voltage and the followings are called reignition voltage if a type 3 or type 4 reignition follows. The zero voltage spike just before a type 2 reignition is called a zero reignition voltage. In order to distinguish the reignition voltages after each reignition, \( U_m \), \( U_{ir} \), etc. are used to stand for the reignition voltage after first reignition, second reignition and so on. \( U_{ir} \) stands for the cold breakdown voltage or initial reignition voltage. The peak value of final recovery voltage \( U_m \) stands for the maximum voltage of TRV after the last reignition in one shot.

The shot shown in Fig.5 contains all the four types of reignitions. The type of each reignition is labelled out at the top in "Type" item. It must be mentioned here that there may be no Type 2, Type 3, or Type 4 in one specific shot.

The measurement is carried out by applying the method described in EXPERIMENTAL SET-UP section. For one set of parameters of (fixed) gap length, value of charging voltage of capacitor C and value of C itself, 5 to 50 shots are made. According to the specific situation three ways are used to transfer data of each shot (see Fig.5) from the oscilloscope waveform to a database.

At first, for some measurements of Cu and CuCr contact materials, (because more information is expected to get from the measurement) all the reignition voltages, the peak value of final recovery voltage and peak values of current of each reignition of all shots are input into a data file. Such a kind of data file is called 'TYPE A' data file. TYPE A data files exist for Cu and CuCr contact materials.

Then it is found that the current decaying process does not change a lot. So in one shot it is possible to get the current values of following half-cycles from the first current value and the decaying time constant. In this case all the reignition voltages and peak values of current of each reignition of the first shot, and all the reignition voltages and the peak value of current of the first reignition of all the following shots are input into data file. All the other current values are calculated from the current of first reignition of each shot through the damping process obtained from the first short. Such a kind of data file is called 'TYPE B' data file. TYPE B data files exist for Cu, CuCr and AgWC contact materials.

At last, because there are a lot of type 4 reignitions of a AgWC vacuum gap, as shown in Fig.6, only the cold breakdown voltage and the final residual voltage over the capacitor of the HF circuit of each shot are input into a data file. This type of data files is called 'TYPE C' data file and only exists for AgWC contact material.

It should be pointed out that TYPE A and TYPE B also contains the sequential number of each reignition in one shot. That is to say a data point contains one sequential
number, one current and one reignition voltage for TYPE A and TYPE B files, and one cold breakdown voltage and one residual voltage over capacitor C for TYPE C data files.

The quantity of data for the different contact materials used in this research is given in Tab.2 and the details of each data file (such as the conditions and parameters of the measurement) is given in APPENDIX B and the data structure is shown in appendix C.

Tab.2  Data volume of the measurement

<table>
<thead>
<tr>
<th>contact material</th>
<th>Cu</th>
<th>CuCr</th>
<th>AgWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>nr. of data files</td>
<td>24</td>
<td>22</td>
<td>7</td>
</tr>
<tr>
<td>nr. of shots</td>
<td>527</td>
<td>555</td>
<td>397</td>
</tr>
<tr>
<td>nr. of data points</td>
<td>5260</td>
<td>4885</td>
<td>1012</td>
</tr>
</tbody>
</table>

The total nr. of data points (lines in the files) is 11157.

The inductance used for all data files is 147.3 $\mu$H and if not mentioned specifically the
$C_o$ takes 400pF. In order to see the effect of very high current and RRTRV on the HF arcing phenomena, a smaller inductance (41.36$\mu$H) is also used but only plots are made, no data have been recorded in files.
4. DATA PROCESSING AND ANALYSIS

When the current of a vacuum arc passes zero and is interrupted the diffusion of the residual plasma causes the recovery of the vacuum gap from the conducting state to the insulating state. There is a race between the speed of dielectric recovery and the rate of rise of transient recovery voltage (RRTRV) which is supplied by the circuit. At the moment the recovery voltage is higher than the momentary voltage withstanding ability of the vacuum gap, the gap will breakdown and the current starts to flow in the vacuum through the residual plasma again. For HF vacuum arc the situation is the same. The extent of the recovery of the vacuum gap after each current zero is reflected by the following reignition voltage (\(u\)).

It is known that the di/dt and the amplitude of the current before current zero have effects on the distribution of reignition voltage \([4, 5, 6, 7]\). The research on the effect of gap length to the reignition phenomena is described in this report.

Fig.7 to Fig.11 show the results of the measurement of CuCr vacuum interrupter with capacitor C being 10nF and gap length being 0.1mm, 0.2mm, 0.3mm, 0.4mm and 0.5mm respectively (data file itcucr10.dat, itcucr20.dat, itcucr30.dat, itcucr40.dat, and itcucr50.dat). In those figures each vertical stripe which expresses the distribution and mean value of reignition voltages (indicted by \(x\)) after a certain numbered current zero is denoted by a number at the top of the stripe, which stands for the sequential
Fig. 8 The measured mean values and distributions of reignition voltages after each current zero for CuCr contact material with d = 0.2mm

Fig. 9 The measured mean values and distributions of reignition voltages after each current zero for CuCr contact material with d = 0.3mm
Fig. 10  The measured mean values and distributions of reignition voltages after each current zero for CuCr contact material with d = 0.4 mm

Fig. 11  The measured mean values and distributions of reignition voltages after each current zero for CuCr contact material with d = 0.5 mm
number of the corresponding current zero. It is to say that the number just mentioned corresponds to the 'n' in 'urn'. When treating the data, the absolute values of reignition voltage are used to draw the figures. So the negative reignition voltages after the odd-numbered current zero (in the case of negatively charged capacitor C after even-numbered current zero) appear positive in the figure like Fig.7 etc. The decaying residual voltage over capacitor C and the peak value of the recovery voltage (urn) are also given in Fig.7. The decaying curve can also represent the decaying current because \( \text{i}_{n} = \text{U}_{c}/\text{Z}_{0} \), where \( \text{Z}_{0} \) is the impedance of HF circuit.

At first glance at the five figures it is clear that the gap length has strong effects on the distribution and mean value of reignition voltage. At small gap length (<0.3mm for the results shown in the figures) the distributions and the mean values of reignition voltages after each current zero are independent of the previous current declining before each successive current zero, whereas \( \text{u}_{r} \) remains more or less a constant. Also, the high average value of \( \text{u}_{r} \) indicates a very small portion of the reignitions consists of type 2, the reignition voltage of which is defined as \( \text{u}_{r}=0 \). This means that at small gap length and current below several hundred ampere the criterion for HF current interruption can be expressed as

\[
\text{U}_{m} < \text{U}_{r}(d)
\]

where \( \text{U}_{m} \) is the prospective maximum recovery voltage the circuit can provide, \( \text{U}_{r}(d) \) the gap length dependent reignition voltage and \( d \) the gap length. In the practical situation, where the gap length is small, \( \text{U}_{r}(d) \) can be expressed as \( \alpha_{r}\text{U}_{b} \), where \( \alpha_{r} \) is the voltage reduction factor and \( \text{U}_{b} \) the momentary cold breakdown voltage of the vacuum gap. This is the conception of the dielectrically dominated HF current interrupting criterion described in Chapter 1.

At larger gap length there are more type 2 reignitions. And the mean values of reignition voltages after even-numbered current zero and the mean values after odd-numbered current zero observe different rules. Specific topics are discussed below.

### 4.1 COLD BREAKDOWN VOLTAGE

For each shot of the measurement the initial breakdown voltage is taken as the cold breakdown voltage. The mean value of the cold breakdown voltage vs gap length for Cu, CuCr and AgWC are shown in Fig.12, Fig.13 and Fig.14 respectively. In the figures the length of the vertical line which coincides with the data point of mean value of cold breakdown voltages is equal to two times of the standard deviation of the corresponding group of data. In the range of gap length used in the measurement the cold breakdown voltages are linear functions of gap length. The relation between \( \text{U}_{b} \) and gap length \( d \) is fitted by \( \text{U}_{b} = \text{a}_{b} \cdot d + \text{a}_{v} \), where \( \text{U}_{b} \) is the cold breakdown voltage (in kV) and \( d \) the gap length (in mm). The coefficient \( \text{a}_{b} \) and \( \text{a}_{v} \) for Cu, CuCr and AgWC are listed in Tab.3. It should be emphasized here that in Fig.12 to Fig.14 the x-axis is only continuous for fitted direct lines. The mean values and deviations of the measured data belonging to the same gap length but different C are drawn in a range which stands for the same gap length. Those ranges are distinguished by a number of horizontal line bars at the bottom of the figures.
Fig. 12  The cold breakdown voltage vs gap length for Cu with C=3.3nF and 10nF

Fig. 13  The cold breakdown voltage vs gap length for CuCr with C=3.3nF, 6.6nF and 10nF
Fig.14 The cold breakdown voltage vs gap length for AgWC with $C=3.3\,\text{nF}$

<table>
<thead>
<tr>
<th>contact material and $C$</th>
<th>$a_e$ (kV/mm)</th>
<th>$a_d$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgWC $C=3.3,\text{nF}$</td>
<td>32.8</td>
<td>-0.7</td>
</tr>
<tr>
<td>Cu $C=10,\text{nF}$</td>
<td>53.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Cu $C=3.4,\text{nF}$</td>
<td>70.8</td>
<td>-1.2</td>
</tr>
<tr>
<td>CuCr $C=10,\text{nF}$</td>
<td>106.3</td>
<td>0.3</td>
</tr>
<tr>
<td>CuCr $C=6.6,\text{nF}$</td>
<td>106.7</td>
<td>1</td>
</tr>
<tr>
<td>CuCr $C=3.3,\text{nF}$</td>
<td>110.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

For CuCr the cold breakdown characteristic is not so sensitive to the capacitor $C$ and for copper the cold breakdown voltage is higher with smaller $C$. It means the voltage withstanding ability of CuCr changes little before and after the arcing of different current compared with Cu. This is why CuCr is widely used in vacuum interrupters to obtain higher voltage withstanding ability after arcing.

From Fig.12 to Fig.14 it looks like that the current of different $C$ (but same $L$) may condition the vacuum gap to a certain level. Then, a further increase in number of shots will not change the cold breakdown voltage any more. A similar phenomenon also happens with voltage in the measurement of cold recovery process of an opening.
vacuum interrupter (measuring the dynamic voltage withstanding ability of a opening cold vacuum gap; the detail of the measuring principle is described in reference 10). For a new vacuum interrupter, if the voltage of the DC power source increases step by step and many measurements are made at each step, the vacuum gap conditioned at a lower voltage stage shows the unconditioned characteristics of a new interrupter in the first several measurements at a higher voltage stage.

It can be concluded that after HF arcing the cold breakdown withstanding ability may change a little with different $C$ for CuCr, but a lot for Cu. Under the condition of this research the CuCr shows much higher cold breakdown voltage than the other two materials do.

4.2 POLARITY EFFECTS

As mentioned above the mean values of reignition voltage after even-numbered current zero and after odd-numbered current zero observe different rules. This phenomenon is called the polarity effect of gap length with respect to the reignition voltage of the HF vacuum arc.

In order to know if the polarity effects is caused by the combination of the polarity of the initially charged voltage of capacitor $C$ and the vacuum interrupter, the capacitor $C$ is charged to a negative voltage by reversing the rectifier. Such kind of measurement is carried out for Cu contact material with $d$ being equal to 0.3, 0.5 and

Fig. 15 The mean values ($\circ$) and distributions (.) of reignition voltages after each current zero for Cu with negatively charged voltage of $C$
The measured mean values and distributions of reignition voltages after each current zero for Cu with negatively charged voltage of C

Fig. 16

The measured mean values (o) and distributions (.) of reignition voltages after each current zero with negatively charged voltage of C

Fig. 17
0.7mm (data file linku30.dat, linku50.dat and linku70.dat). The result of such measurement is shown in Fig.15 to Fig.17. The figures show that at small gap length the mean values of the reignition voltages after odd-numbered and even numbered of current zeroes observe the same rule as in the case of positively charged capacitor. At large gap length there is a polarity effect. So it can be concluded that the polarity effects on reignition voltage at large gap length is really a characteristic of HF vacuum arc. It must be mentioned here that all the results of the measurements listed in APPENDIX B show the same tendency.

It is difficult to explain in detail the mechanism which controls the phenomenon. From Fig.7 to Fig.11 it is clearly seen that the phenomena occurs at larger gap length and therefore at higher cold breakdown voltage.

In Fig.5 there is always a current spike at the beginning of each reignition current as long as the reignition is not type 2. This current spike is caused by the discharge of the capacitor Cc. In order to demonstrate this an extra capacitor of 500pF is paralleled to the vacuum interrupter. The connection wire is put through the current transformer (CT) so the current caused by the extra capacitor can be measured. Fig.18 is the measured current and voltage waveform. It is clearly seen that an oscillating waveform is superimposed on both the voltage and current of HF arc. Connecting a resistor (Rc) in series (100Ω) with the extra capacitor the oscillation becomes an current spike like in Fig.5. In Fig.4 the high voltage signal cable also acts as a capacitor and the 50Ω characteristic resistor as a oscillation damper. In practical circuit there is always a parasitic capacitor paralleled to the vacuum interrupter but usually much smaller than

![Fig.18](image-url)
the introduced capacitance by the voltage divider in this research. It is concluded that the current spike comes from the discharge of the local capacitor ($C_o$).

The amplitude of this current spike should be proportional to the corresponding reignition voltage. At the instant of cold breakdown of the vacuum gap, because of the higher cold breakdown voltage, this current spike is at maximum. Especially when the gap length is large, very high current can result: $I_c = u_c/R_c$ can be up to 800A at 40kV.

From Fig.9 to Fig.11, it is clear that the polarity effects fades away with the increase of arcing time or the number of half-cycles of HF arcing. So it is possible to conclude that the polarity effect is the result of the effect of the cold breakdown voltage which through the large current spike can cause the deformation on the surface of one of the two electrodes.

The dynamic effect of the initial current spike is defined as the effect the result of which decays naturally (e.g. the thermal effect of the cooling of the heated surface) and the static effect as the one that results would be permanent if there were not following conditioning arc (e.g. formation of micro-protrusion by first current spike). There is no direct proof right now if the effect of the first current spike is dynamic or static, but from the duration (larger than several half-cycles of the HF arc) of the effects it is reasonable to consider the effects static.

It looks like that the cold breakdown causes serious deformation of the contact surface on the initial anode which favours the following reignition for which the initial anode is the new cathode. The deformation is being reduced away by the following arc and its function vanished after a number of half-cycles of HF arcing.

4.3 GAP LENGTH DEPENDENT REIGNITION VOLTAGE

It is clear that the polarity effects caused by gap length causes more type 2 reignitions after odd-numbered current zero. What does the gap length do with the reignition voltages after the even-numbered current zero? The authors believe that the distribution or the mean value of reignition voltages after even-numbered current zero reflects the behaviour of HF vacuum arc under the influence of gap length.

The percentage of type 3 is considered as one sign which reflects the characteristics of HF vacuum arc. In order to have an overlook of the dependence of the percentage of type 3 reignitions to the gap length and the peak value of the previous current of HF arcing the percentage of type 3 reignitions after even-number of current zero against the mean value of previous current for different gap length are drawn in Fig.19 to Fig.24.

The figures are created in such a way that for each data file of different gap length the data is divided into a number of groups according to which sequential number of current zero that follows (for reignition voltage) and which sequential number of current that proceeds (for current). The data belong to odd-number of current zero is deleted. As for the data belonging to even-number of current zero, the mean value of the
current belonged to one current zero is considered the current value of one point in Fig.19 to Fig.24 and the reignition voltages belonged to the same current zero are used to obtain the percentage of type 3 reignitions. A voltage of 1kV is used to divide the reignition voltages into two parts according to if the reignition voltage is larger or smaller than 1kV. The number of the group of voltage smaller than 1kV is \( n_2 \) (type 2) and the number of the group larger than or equal to 1kV \( n_3 \) (type 3). The percentage of reignition voltage after the particular current zero is calculated through the equation \( P_3 = \frac{n_3}{n_3 + n_2} \) and is the percentage value of the corresponding point in Fig.19 to 24.

Direct lines are used to fit the data because it is easy to see the tendency in this way. In those figures the points at the right end of each line also stand for the maximum current in the corresponding data file (abscissa) and the points at the left end for the minimum one.

From Fig.19 to Fig.24 it is clearly seen that in each figure the percentage of type 3 reignitions after an even number of current zero decreases as gap length and previous current increase. The result of AgWC contact material in Fig.24 shows abnormal tendency. This is because the dielectric recovery of an AgWC vacuum interrupter is much more random. Fig.25 gives the current and voltage waveform of a shot for AgWC with \( C = 10\text{nF} \), \( d = 0.6\text{mm} \) and the pre-charged voltage of \( C \) being 20kV. The peak value of current of the first reignition is 156A and the cold breakdown voltage is 14kV. The reignition voltage after first and second current zero reach to quite high level and then there are 6 type 2 reignitions. Because of the zero reignition voltage the corresponding reignition current does not contain a current spike at the beginning.
Fig. 20  Percentage of type 3 reignitions against the peak value of last current for Cu with different gap length (C=3.3nF)

Fig. 21  Percentage of type 3 reignitions against the peak value of last current for CuCr with different gap length (C=10nF)
Fig. 22 Percentage of type 3 reignitions against the peak value of last current for CuCr with different gap length (C=6.6nF)

Fig. 23 Percentage of type 3 reignitions against the peak value of last current for CuCr with different gap length (C=3.3nF)
Fig. 24  Percentage of type 3 reignitions against the peak value of last current for AgWC with different gap length (C=3.3nF)

Fig. 25  The voltage and current waveform of a measurement for AgWC with abnormal reignition characteristics. Current: 60A/div, voltage: 6.05kV/div, time: 5μs/div
From Fig.19 to Fig.24 it is clear, both for Cu and CuCr that for the same current the percentage of type 3 reignitions increases with C. Because larger C means larger quantity of transferred electrical charge through the vacuum gap in one half-cycles of HF arc, it looks like that the erosion effect of the arc to the surface of the contact decreases the probability of occurrence of type 2 reignition. It can be concluded that the deformation of contact surface also has effects on the reignition voltages after even-number of current zero.

The gap length dependent reignment characteristic is further confirmed by Fig.26 to Fig.29. They are measured from CuCr material with a small inductor (41.4μH instead of 147μH) as described in the chapter of EXPERIMENTAL SET-UP and different gap length (0.1mm for Fig.26, Fig.27 and 0.4mm for Fig.28, Fig.29). The peak value of current of the first reignition in Fig.26 and Fig.27 is 884A and 869A, and the peak value of current of second reignition in Fig.27 and Fig.29 is 900A and 860A respectively. In the case of small gap length there are more type 3 reignitions than in large gap length so that there are more voltage spikes on the voltage waveform.

The conclusion of the above discussion is that the percentage of type 2 reignitions increases with gap length.

Fig.26
The waveform for showing the gap length dependent percentage of type 3 reignitions. current (upper trace): 240A/div voltage: 7.6kV/div time: 5μs/div (CuCr d=0.1mm L=41.4μH C=20nF)
Fig. 27  The waveform for showing the gap length dependent percentage of type 3 reignitions. current (upper trace): 240A/div voltage: 7.6kV/div time: 5μs/div (CuCr d=0.1mm L=41.4μH C=20nF)

Fig. 28  The waveform for showing the gap length dependent percentage of type 3 reignitions. current (upper trace): 240A/div voltage: 15kV/div time: 5μs/div (CuCr d=0.4mm L=41.4μH C=20nF)
The waveform for showing the gap length dependent percentage of type 3 reignitions. current (upper trace): 240A/div voltage: 15kV/div time: 5μs/div (CuCr d=0.4mm L=41.4μH C=20nF)

4.4 INTERRUPTING ABILITY OF HF VACUUM ARC

The interrupting ability of HF arcing can be expressed in several ways. It has been known from previous research that for current being not very high the interruption depends on the question if the prospective maximum value of final UHF-TRV $U_m$ is less than the reduced momentary breakdown voltage. So reduced momentary breakdown voltage and interrupted $U_m$ is a reflection of interrupting ability. In this report the interrupting ability is expressed in two ways, one being the final maximum recovery voltage $U_m$ against the cold breakdown voltage $U_c$ and the other $U_m$ against gap length. The reason is that the authors want to give further support to the previous dielectrically dominated HF current interrupting criterion described in the chapter of INTRODUCTION and so want to know if there are big differences between the two ways (e.g. maybe conditioning effect may increase cold breakdown voltage but not increase the interrupting ability).

Fig.30 and Fig.31 give the final interrupted $U_m$ against cold breakdown voltage $U_c$ for Cu and CuCr, and Fig.32 and Fig.33 the $U_m$ against gap length ($d$). In those four figures each point represent a pair of $U_m$ and $U_c$ or $d$ and the mean values are calculated for the data belong to each gap length. At large gap length (>0.4mm) there seems to be some different conditioning effects of different HF current which is produced by different C. This is shown in Fig.30 and Fig.31. It must be mentioned here that the real sequence of measurement for Cu is "ltcu*.dat, liicu*.dat" and for CuCr is...
The peak value of final recovery voltage $U_m$ against cold breakdown voltage $U_b$ for Cu with different C:

**Fig. 30**

The peak value of final recovery voltage $U_m$ against cold breakdown voltage $U_b$ for CuCr with different C:

**Fig. 31**
Fig.32 The peak value of final recovery voltage $U_m$ against gap length $d$ for Cu contact material

Fig.33 The peak values of final recovery voltage against gap length $d$ for CuCr
"licucr*.dat, zhcucr*.dat, and ltcucr*.dat". The asterisk "*" stands for any numerical character in the name of data file in APPENDIX B. So the higher mean value of $U_m$ is not caused by the sequence of measurement.

There is nearly no difference between the two ways in those four figures for gap length is smaller than 0.3mm.

From those figures the conclusion is that the interrupting ability of a HF vacuum arc is roughly proportional to the cold breakdown voltage of the same gap. So if a decaying HF current can be interrupted after a particular current zero depends on if the peak value of the following recovery voltage is smaller or larger than the reduced momentary cold breakdown voltage.

The relation between $U_m$ and $d$ can be expressed as

$$U_m = 0.4 + 91d - 67.3d^2 \quad \text{(for CuCr)}$$

(1)

and

$$U_m = 0.8 + 59.8d - 20.1d^2 \quad \text{(for Cu)},$$

(2)

where $U_m$ in kV and $d$ in mm.

Fig. 34 The measured mean values and distributions of reignition voltages after each current zero for CuCr with $d=0.3$mm $C_0=400pF$
The measured mean values and distributions of reignition voltages after each current zero for CuCr with $d=0.3\text{mm}$ and $C_0=2900\text{pF}$

The measured mean values and distributions of reignition voltages after each current zero for CuCr with $d=0.3\text{mm}$ and $C_0=5400\text{pF}$
The measured mean values and distributions of reignition voltages after each current zero for CuCr with $d=0.4\text{mm}$ and $C_0=400\text{pF}$

Fig. 37

The measured mean values and distributions of reignition voltages after each current zero for CuCr with $d=0.4\text{mm}$ and $C_0=1900\text{pF}$

Fig. 38
The measured mean values and distributions of reignition voltages after each current zero for CuCr with \( d = 0.4\text{mm} \) and \( C_0 = 2900\text{nF} \)

Fig. 39

The measured mean values and distributions of reignition voltages after each current zero for CuCr with \( d = 0.4\text{mm} \) and \( C_0 = 5400\text{nF} \)

Fig. 40
Now the question can be put forward if the interrupting model derived from one set of circuit parameters fits other circuit conditions too. For example, the rate of rise of transient recovery voltage (RRTRV) is not the same in different circuits. In order to investigate the sensitivity of the interrupting model to RRTRV measurements are made for CuCr with different gap length and \( C_0 \). The results are shown in Fig.34 to Fig.40 (ztcr3c0.dat, ztcr3c25.dat, ztcr3c5.dat, ztccucr40.dat, ztcr4c15.dat, ztcr4c25.dat and ztcr4c5). The gap length, \( C \) and \( C_0 \) are given in each figure.

For the gap length being both 0.3mm (Fig.34-Fig.36) and 0.4mm (Fig.37-Fig.40) it is easily seen that the function of \( C_0 \) is to reduce the number of half-cycles of HF arcing but little to final peak value of recovery voltage \( U_m \). For concision, the \( U_m \) for different \( C_0 \) are drawn in Fig.41.

The calculated average RRTRV for different \( C \) and \( C_0 \) is shown in Fig.42. In the calculation the residual voltage of capacitor \( C \) is taken as 40 kV and the overshoot factor is taken as 1.5, the mean value of the circuit. If the residual voltage over capacitor \( C \) is \( U_{residual} \) the RRTRV should be the reading of Fig.42 times \( U_{residual}/40 \text{kV} \). From Fig.42 it is obvious that for \( C=20 \text{nF} \) when \( C_0 \) increases form 400pF to 5400pF the RRTRV decreases about four times. In Fig.41 the peak value of final TRV only change a little. It looks like that in the range of this research the peak value of final TRV depends little on RRTRV.

From the above discussion, it can be concluded that for a current less than several hundred amperes the extinction of HF vacuum arc depends largely on the question...
Fig. 42  The calculated RRTRV of the test circuit

if the peak value of TRV is less than a threshold voltage the value of which is proportional to gap length and therefore to cold breakdown voltage. This fully supports the dielectrically dominated interrupting model mentioned at the beginning of this section.

It should be emphasised that the dielectrically dominated interrupting model only fits AgWC contact material when the maximum current is less than about 72 amperes [9]. If the maximum current is higher than 95 amperes the HF arc behaves abnormal. This is shown in Fig. 25 (the maximum current is 156 A) and in Fig. 43 to Fig. 47. Fig. 43 to Fig. 46 (ltagw20.dat, liagwc40.dat, liagwc60.dat and liagwc80.dat) show that at the gap length larger than 0.4mm and after the polarity effect has been decayed away the mean value of the reignition voltage against sequential number of current zero appear little a 'V' shape. This means more type 2 reignitions appear at certain sequential number of current zero. Fig. 47 (ltagw40.dat, ltagw60.dat and ltagw80.dat) shows the result of data file ltagwc40.dat, ltagwc60.dat, and ltagwc80.dat for AgWC contact material. At large gap length the residual voltage of capacitor C can be very high (15kV) or very low (<1kV). So the conclusion can be obtained that at large current (>72A for AgWC) the dielectrically dominated interrupting model does not apply and the HF current interrupting ability of vacuum gap is more random.
Fig. 43  The measured mean values and distributions of reignition voltages after each current zero for AgWC with \( d = 0.2 \text{mm} \)

Fig. 44  The measured mean values and distributions of reignition voltages after each current zero for AgWC with \( d = 0.4 \text{mm} \)
The measured mean values and distributions of reignition voltages after each current zero for AgWC with $d=0.6\text{mm}$

The measured mean values and distributions of reignition voltages after each current zero for AgWC with $d=0.8\text{mm}$
The relation between residual voltages of capacitor C and cold breakdown voltage for AgWC with d=0.4, 0.6 and 0.8mm

4.5 NUMBER OF HALF-CYCLES OF HF ARCING

The measured number of half-cycles of HF arcing is shown in Fig.48 and Fig.49. In these two figures the gap length d is shown at the top of the figure. The figures also show the cumulative distribution of number of half-cycles. Take Fig.48 for example, in the range of d=0.1mm, the left boundary stands for 0% and the right boundary for 100%. The dots are the measured data and they are fitted with a normal distribution function. From the figures, it is obviously seen that the number of half-cycles of HF arcing increases with C and decreases as gap length increases. Because the period of HF arcing increases as C increases, the arcing time would increase much more with C. This must be kept in mind when estimation of reignition or virtual current chopping overvoltage is under consideration because longer HF arcing time would allow load inductance being charged to a higher value of current[9].

The question here is why the number of half-cycles is larger for a large C than for a small C. In Fig.1, when the switch SW is closed the voltage across VI will increase to the cold breakdown voltage and at the same time the parasitic capacitor paralleled to the vacuum gap is charged to the same voltage. When breakdown of the vacuum gap occurs the energy of this capacitor will immediately be dissipated into the vacuum gap. The reignition voltage does the same with this capacitor. In Fig.5 a current spike at the beginning of each half-cycle of HF current is the result of such energy dissipation. This energy must be taken into account when analyzing the HF arcing phenomena.
Fig. 48  The measured mean values and distributions of number of half-cycles of HF vacuum arcing for Cu with different gap length.

Fig. 49  The measured mean values and distributions of number of half-cycles of HF vacuum arcing for CuCr with different gap length.
In a RLC circuit the voltage across the capacitor can be written as,

\[ U_c(t) = U_c(0) \exp(-a_1 t) \cos(\omega t) \]  

where \( a_1 = R/2L \) is the decaying constant and \( \omega = 1/\sqrt{LC} \) is the angular frequency of the oscillation. If only the values of voltage of capacitor at each current zero are under consideration, the voltage \( U_c \) can also be expressed as,

\[ U_c(n) = U_c(0) \exp(-a_n \cdot n) \]  

where \( n \) is the sequential nr. of current zero at which the voltage is measured. The relation between \( a_n \) and \( a_1 \) is,

\[ a_n = 0.5 \pi \frac{a_1}{\omega} \]  

For the circuit shown in Fig.1, if there is an arc between the contacts in VI the effect of \( C_o \) to the HF circuit will scarcely exist because the arc voltage is very low compared with the residual voltage of capacitor \( C \). So the circuit will work according to the principle described above. To a certain extent the function of \( C_o \) (including the paralleled parasitic capacitance) is to dissipate some energy immediately at the beginning of a reignition (if reignition voltage exist) and to decide if the following reignition will happen. (because in principle the RRTRV and \( U_m \) will be affected by \( C_o \)).

From the view point of energy conservation, the number of half-cycles of HF arcing can be determined as follows. The energy stored in capacitor \( C \) before HF arcing is \( \frac{1}{2} C U_c(0)^2 \). If there is not vacuum gap in HF circuit, that is to say the circuit only consists of \( R, L \) and \( C \), the energy stored in capacitor \( C \) at each HF current zero can be expressed as

\[ E_c(n) = \frac{1}{2} C [U_c(n)]^2 \]

\[ = \frac{1}{2} C [U_c(0) \exp(-a_n n)]^2 \]

\[ = E_c(n-1) \exp(-2a_n) \]  

Considering the vacuum gap in the circuit, the energy dissipation caused by reignition voltage \( U_r(n) \) and the capacitor paralleled to vacuum interrupter \( C_o \), \( E_c(n) \) must be taken in to account. It is known from the measurement that the energy dissipation by \( U_r \) is very fast (in the time of less than one tenth of the period of HF circuit). So it is reasonable to consider \( E_c(n) \) a integral energy loss at the beginning of each half cycle of current (reignition). So,

\[ E_c(n) = (E_c(n-1) - E_r(n)) \exp(-2a_n) \]  

and the voltage of the capacitor \( C \) at each current zero will be

\[ U_c(n) = \sqrt{U_c^2(n-1) - \frac{C_o}{C} U_r^2(n-1) \exp(-2a_n)} \]
If the overshoot factor of the circuit is $f_p$, the maximum recovery voltage which the circuit can provide at $n$-th current zero is $U_c(n) f_p$. So

$$U_c(n) f_p > U,$$

(9)

is the criterion of the occurrence of $n$-th reignition. The number of half-cycles of HF arcing will increase one by one until the condition of the equation 9 is not satisfied any more.

It must be emphasized that it was found in the measurement that the decaying constant $a_i$ is a function of the frequency of HF circuit. This is because the energy radiated in the form of an electromagnetic wave and the skin effect increases with the frequency.

The inherent decaying constant of the circuit is defined as the decaying constant when the reignition voltage is zero. The inherent decaying constant can be measured in the experimental circuit. It should be mentioned here that the decaying constant $a_i$ and $a_r$ mentioned above are inherent decaying constants.

The measured $a_i$ for different $C$ is listed in Tab.4.

<table>
<thead>
<tr>
<th>$C$ (nF)</th>
<th>30</th>
<th>20</th>
<th>10</th>
<th>5</th>
<th>3.3</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i$ (1/s)</td>
<td>2.04e4</td>
<td>2.63e4</td>
<td>4.15e4</td>
<td>6.13e4</td>
<td>7.65e4</td>
<td>7.67e4</td>
</tr>
</tbody>
</table>

It is obviously seen that the $a_i$ increases with the frequency of HF circuit. Fig.50 shows the relation between $a_i$ and frequency $f$. It can be concluded that in the range of frequency used in the measurement the relation between $a_i$ (in 1/s) and frequency $f$ (in Hz) can be expressed as a linear equation,

$$a_i(f) = b + a f$$

(10)

where $a = 0.35$ and $b = -2.4e3$. It means that in the high frequency situation the decaying constant is determined by the frequency rather than the measured circuit resistance at low frequency or DC. The frequency dependent $a_i$ phenomenon can be considered as a frequency dependent resistance phenomenon. For a HF oscillation circuit

$$a_i(f) = R_{if}/2L$$

where $R_{if}$ is the HF resistance, so

$$R_{if} = a_i \cdot 2L = (b + a \cdot f) \cdot 2L$$

is a frequency dependent resistance. When apply the theoretical method to estimate the overvoltage of a real circuit it is important to consider the frequency dependant
The measured relation between $a_i$ and frequency $f$ for the test circuit decaying constant $a_i$, because the calculated $a_i$ (only from inductance $L$ and $R$) is not the real decaying constant and is smaller than the real one.

The calculated number of half-cycles of HF arcing are shown in Fig. 51 (for Cu) and Fig. 52 (for CuCr). In the calculation $U_i(n)$ takes one value which is equal to the mean value of final peak value of recovery voltage $U_m$ given by equation 1 (for Cu) and equation 2 (for CuCr). The inherent decay constant comes from equation 10. The matlab program for calculating the number of half-cycles of vacuum arcing is given in APPENDIX D.

When considering the random characteristics of $U_i(n)$, the calculation should be repeated many times and the distribution of reignition voltage to simulate the real situation should be considered. Nevertheless, the qualitative and quantitative agreement between measurement and calculation is satisfying.

From the above discussion it can be concluded that the number of half-cycles of HF arcing is affected by the contact material and gap length (through $U_i(n)$ in the model), HF circuit parameters (through $a_i$ in the model), parasitic capacitor (including the capacitor deliberately paralleled to vacuum interrupter) $C_o$ and the initial voltage of capacitor $C$ (or energy stored in capacitor) $C$. In the range of frequency used in the measurement, the number of half-cycles of the HF vacuum arc increases with $C$, $C_o$ and $U_c(0)$, and decreases as gap length increases. Both the result of measurement and theoretical analysis meet each other. This further confirms the dielectrically dominated HF current interruption criterion.
The calculated number of half-cycles of HF vacuum arcing for Cu with different gap length

The calculated number of half-cycles of HF vacuum arcing for CuCr with different gap length
4.6 Post-arc current

The post-arc current is not the content of this research but some phenomena are seen during the measurement. For describing the phenomena explicitly the post-arc current is divided into two types, the post-arc current after the last HF reignition (TYPE AL) and post-arc current before the last reignition (TYPE BL). This is because TYPE BL post arc current may not reach it maximum when the next reignition occurs. The waveforms of current and voltage are shown in Fig.53 (a) and (b). There are four TYPE BL post arc currents and, of course, one TYPE AL post-arc current. It is found that at large gap length (>0.5mm) there are frequently TYPE AL post-current with quite high peak value (25A). But at small gap length there is no obvious TYPE AL post-arc current (less than 2A). The general conception obtained is that the TYPE AL post-arc current is a random phenomena and at large gap length the post-arc current is larger than at small gap length.

From Fig.53 (b) it is obvious that the final recovery voltage is far from an oscillating waveform. This is because the large post-arc current has strong effects on the waveform of recovery voltage.

Fig.53 is a special voltage and current waveform because it contains many phenomena of HF vacuum arc such as delayed cold breakdown of the vacuum gap, reignition and post-arc current etc.. So it can be used to demonstrate the complicated behaviour of the vacuum arc.
The current waveform of a measurement with post-arc current and delayed cold breakdown of the vacuum gap.

The voltage waveform of a measurement with post-arc current and delayed cold breakdown of the vacuum gap.
5. SUMMARY AND CONCLUSIONS

1. More than 11,000 measurements were carried out in a 40 kV circuit in order to investigate the essential parameters of HF current interruption in vacuum interrupters. A special HVDC circuit was constructed to study the influence of gap length and HF arcing stress on the interruption process separately. In conventional test circuits, employing opening contacts, such a separation is not possible.

2. The cold breakdown voltage of vacuum interrupters having a fixed gap length was measured with a 650 kHz impulse 60 kV voltage. For a gap length less than 1 mm the following breakdown field strengths were found for the three contact materials under study:
   - Cu: \( 534 \text{kV/cm} < E_b < 708 \text{kV/cm} \)
   - CuCr: \( 1063 \text{kV/cm} < E_b < 1109 \text{kV/cm} \)
   - AgWC: \( E_b = 328 \text{kV/cm} \)
   At small gap length (< 0.9 mm) the effect of a HF arc of several 100 kHz and several hundred A is observed to increase the cold breakdown voltage.

3. It was found that in the range of HF current amplitude investigated (up to 370 A), the duration of the HF arc is mainly determined by the ability of the TRV (following HF current interruption) to cause breakdown of the vacuum gap. Thus, arc duration is directly related to the breakdown voltage of the gap, together with the HF circuit's ability to provide the necessary voltage in order to exceed the breakdown voltage.
   From our findings, the sole criterion for HF current interruption ability is a dielectric one, in contrast to the conventional \( \text{di/dt} \) criterion. However, this is only valid for sufficiently fast rising TRV, such as occur in practical power systems (several 100 kV/\( \mu \text{s} \)).
   As for the various contact materials, Cu and CuCr showed the behaviour as described above in a more regular way than AgWC, the latter showing more erratic characteristics.

4. Based on the above idea, a calculation (on a semi-empirical basis) of the arc duration was made that fits the measured values well.

5. For larger values of the gap length (> 0.6 mm), the share of reignitions that do not require a high voltage to start (type 2) increases. This observation coincides with the occurrence of a (sometimes very large, up to 20 A) post arc current after HF current zero.

6. Because of the importance of dielectric processes the time constant of voltage decay on the HF current driving capacitor is a very important parameter. In modelling, the frequency dependence (due to the skin effect and electromagnetic radiation) of this time constant must therefore be taken into account. This was clearly shown in the measurements.
7. A polarity effect in HF current interruption ability has been found: odd-numbered current zeroes of the HF arc are more likely to be followed by a reignition than the even numbered current zeroes. This effect may be explained by the discharge of a parasitic capacitor ($C_0$) over the vacuum gap. The current due to this discharge (up to 1 kA), may alter the contact surface in such a way as to reduce the ensuing reignition voltage. The parasitic capacitor has a value of at least 400 pF and mainly originates from the way the voltage is measured. Therefore, the polarity effect may be an artefact of the measuring system and it may have no impact on HF arcing phenomena in power distribution circuits.
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TYPES OF REIGNITION FOLLOWING HIGH-FREQUENCY CURRENT ZERO IN VACUUM INTERRUPTERS WITH TWO TYPES OF CONTACT MATERIAL.
APPENDIX A: THE PARAMETERS OF THE MAIN COMPONENTS AND INSTRUMENTS USED IN THE MEASUREMENT PROGRAMME

Oscilloscope: Lecroy dual 125MHz, model 9400. sensitivity 5mV/div to 5V/div (1MΩ), bandwidth DC 0-125MHz (-3dB), input impedance 1MΩ; <30pF, maximum input voltage 250V, 1 AD-converter per channel, 8-bit, 100M samples/sec, memory 32,000 8-bit bytes per channel, timebase 2ns/div to 100sec/div.

Current transformer: Pearson Electronics Inc., model 410, output 0.1V/A (reduced to 0.5 by 50Ω termination), maximum peak current 5,000A, rise time 20ns, IT Max 0.5 A-second, maximum rms current 65A, approx. 3dB pt. 1Hz (low) 20MHz (high).

High voltage probe (used to calibrate the self-made one): Tektronix P6015 probe, attenuation ratio 1000:1 (variable by about 9%), input resistance 100MΩ, input capacitance approx. 3pF, maximum input voltage 20kV (DC or RMS) 40kV (pulse, maximum duty factor 10%, maximum pulse duration 0.1s), bandwidth DC to 75MHz (-3dB), rise time approx. 4.67ns, temperature range -10°C to 55°C, length of the inter­connecting cable 10ft.

Self-made capacitive voltage divider: Ratio 6,050, rise time approx. 50ns, input voltage > 80kV (pulse). High voltage arm: 10 ceramic capacitors (LCC 500pF TE 20kV eff HTD) in series. Low voltage arm: 4 capacitors (0.1μF) in parallel. High voltage signal cable: model F&G-214/U, length 2.6m, capacitance 96.8pF/m. Low voltage signal cable: model F&G RG-58 C/U, length 3.5m.

Capacitor in HF circuit: TTP 7761 8031, 30kV DC, 10nF, 3nF, 5nF.
### APPENDIX B: LIST OF DATA FILES

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<th>C (nF)</th>
<th>(C_0) (pF)</th>
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APPENDIX C: DATA FILE STRUCTURE

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The first shot of Itcucr40.dat

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*The first row of the third column is the cold breakdown voltage.
**The last row of the third column is the final $U_m$.
***The last row of the second column is zero otherwise it is a post arc current (maximum value).
2. liicu50.dat (TYPE B)

The first two shots of liicu50.dat

<table>
<thead>
<tr>
<th>series nr. of each reignition in a shot</th>
<th>current (x20A)</th>
<th>reignment voltage (x6.05kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.14</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>-8.12</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>6.88</td>
<td>4.59</td>
</tr>
<tr>
<td>3</td>
<td>-6.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>5.62</td>
<td>0.56</td>
</tr>
<tr>
<td>5</td>
<td>-5.16</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>4.53</td>
<td>1.31</td>
</tr>
<tr>
<td>7</td>
<td>-4.06</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>4.41</td>
</tr>
</tbody>
</table>

The second shot of liicu50.dat*

<table>
<thead>
<tr>
<th>series nr. of each reignition in a shot</th>
<th>current (x20A)</th>
<th>reignment voltage (x6.05kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.26</td>
<td>4.22</td>
</tr>
<tr>
<td>1</td>
<td>8**</td>
<td>-3.19</td>
</tr>
<tr>
<td>2</td>
<td>8**</td>
<td>5.25</td>
</tr>
<tr>
<td>3</td>
<td>8**</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>8**</td>
<td>6.19</td>
</tr>
</tbody>
</table>

* From the second shot of the data file only the first current is input.
** The number '8' in other current position has no meaning.
3. Itagwc80.dat (TYPE C)

The first column are cold breakdown voltages (x6.05kV).
The second column are residual voltage of capacitor C after HF arcing.

the first five lines of Itagwc80.dat

<table>
<thead>
<tr>
<th>cold breakdown voltage (x6.05kV)</th>
<th>residual voltage of capacitor C (x6.05kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.85</td>
<td>0.49</td>
</tr>
<tr>
<td>-4.41</td>
<td>0.42</td>
</tr>
<tr>
<td>-4.31</td>
<td>1.2</td>
</tr>
<tr>
<td>-4.5</td>
<td>0.66</td>
</tr>
<tr>
<td>-4.41</td>
<td>-0.28</td>
</tr>
</tbody>
</table>
APPENDIX D: THE MATLAB PROGRAM FOR CALCULATING THE NUMBER OF HALF-CYCLES OF HF ARCING

```matlab
plot(0,0,9,25); %make frame;
hold on; %fix the frame;
ll=147e-6; %inductance of HF circuit;
cc=10e-9; %capacitance of HF circuit;
c0=0.4e-9; %parasitic capacitance paralleled to vacuum interrupter;
ff=1/(2*pi*sqrt(ll*cc)); %the frequency of HF circuit;
at=0.3478*ff-2.3805e3; %the measured relation between at and frequency;
an=0.5*pi*sqrt(ll*cc)*at; %calculate an;
uc(1)=40; %the initially charged voltage of cc;
nn=0; %nn is a vector of Dr. of HF arcing at different d;
for ii=1:9, %for Cu and C=10nF;

uri=0.7791+59.8203*(ii/10)-20.0640*(ii/10)*(ii/10);%for Cu and d=ii/10;
%uri=0.4119+90.9929*(ii/10)-67.2619*(ii/10)*(ii/10);%for cucr;
for kk = 2:35, %determine at which current zero the HF arc will extinguish;
uc(kk)=sqrt((uc(kk-1)\^2-c0/cc*uri\^2)*exp(-2*an));
if uc(kk) * 1.5 > uri, nn(ii)=kk;end;
end;
end;
x=0.5:1:8.5; %for cu and C=10nF;
%\(x=0.5:1:6.5; \) %for cu and C=3.3nF;
%\(x=0.5:1:4.5; \) %for cucr;
plot(x,nn,nn,'o');
meta cuthcycl.met; %create plot file;
hold off;
end.
```
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