THE INFLUENCE OF THE STRIKER WIRE ON THE VOLTAGE RISE AFTER THE BEGINNING OF THE ARCING PROCESS IN HV FUSE LINKS

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Abstract: When N rows of constrictions of a melting element are cut by a short circuit current, the arcing voltage starts with the value $u_{ME} = N*U_E$. In this moment a well defined amount of the current is directed across the striker wire. Breaking tests with HV fuse links show that the arcing voltage along the melting element is limited to the voltage drop along the striker wire. The arcing process of the melting element is delayed, until the shunted current has built up the melting integral of the striker wire. For small rated currents the striker wire causes a pause up to 0.4 ms in the arcing process of the melting element.

Wenn ein Kurzschlußstrom N Engstellenreihen eines Schmelzleiters unterbrochen hat, beginnt die Lichtbogenspannung mit dem Wert $u_{ME} = N*U_E$. In diesm Augenblick weicht ein festgelegter Teil des Stromes auf den Kennmelderdraht aus.Schaltversuche mit HH-Sicherungen zeigen, daß die Lichtbogenspannung über den Schmelzleiter begrenzt wird durch den Spannungsfall längs des Kennmelderdrahtes. Der Lichtbogenvorgang beim Schmelzleiter wird verzögert, bis der parallele Strom das Schmelzintegral für den Kennmelderdraht erreicht hat. Für kleine Nennströme verzögert der Kennmelderdraht den Lichtbogenvorgang beim Schmelzleiter bis zu 0.4 ms.

1 INTRODUCTION

When the arcing process in a fuse link is analysed there must be no striker wire in parallel to the melting element in order not to disturb the analysing. The result therefore cannot be transferred to a fuse with a melting element and a parallel striker wire inside. We look at a short circuit current I_2 in a RL-circuit that contains a fuse. The resistance of the striker wire is higher than that of the melting element. When the voltage creats the necessary current, the striker wire will be heated up and interrupted. For big rated currents only a small part of the current will flow along the striker wire and influence little the arcing process in the melting element. For small rated currents the influence lasts remarkably longer. When the voltage along the fuse beginns to rise, the current along the striker wire is still small.

For fuses with small rated currents the pause in the voltage rise may reach several 100 microseconds. The diagram 1 shows the beginning of the arcing process in a HH-fuse with a rated current of 20 A..

2 THE BEGINNING OF THE ARCING PROCESS

A lot of evaluations of breaking tests with fuses lead to the expression of an electrode effect voltage U_E. The moment arcing starts in quartz sand as a arc quenching medium, in each interrupted constriction of the melting element the electrode effect voltage $U_E = 55$ V is created [2]. When a short circuit current interrupts N rows of constrictions of a melting element, the arcing voltage along the melting element starts with the value

$$u_{ME} = N*U_E \tag{1}$$

The voltage u_{ME} along the melting element acts against the test voltage. The melting current i_M creats a voltage drop along the circuit resistance R and reduces the active test voltage. When the current decreases, the voltage u_L across the inductivity L rises in order to have the current unchanged.. At the melting element you measure the voltage $u_{ME} = u_B - R*i_M - L*di/dt$. The voltage u_{ME} creates a current i_{SW} in the parallel striker wire. This current is missed for the build up of the arc resistance in the interruptions of the melting element. A breaking test with a fuse link as described in the annex delivered a melting current $i_M = 1000$ A and a melting integral $i^2t = 869\ A^2s$. The rated current of that fuse is below 20 A.

The current along the melting element is $i_{ME} = i_M - i_{SW}$. We assume the current i_{SW} along the striker wire to be constant. The resistance R_X of the melting element in the moment the constrictions disrupt, can be calculated.

$$R_X = N*U_E / (i_M - i_{SW}) \tag{2}$$

The current i_{ME} vaporizes the material next to the interruptions and creates additionally an arc resistance R_{LB} across each interruption.. The resistance R_{ME} along the melting element grows according to $R_{ME} = R_X + R_{LB}$. The current along the melting element must be big enough in order to build up the isolating distance needed for the maximum arc voltage. We assume to have a fuse with small rated current. When the striker wire is heated up, we assume the resistance of the melting element to be constant. The arc voltage along the melting element rises slowly. The interruptions in the melting element also grow slowly. The danger of reignition rises too. Only when the striker wire disrupts, the arc voltage can rise remarkably.

3 THE STRIKER WIRE

The striker wire has a higher resistance than the melting element. A short circuit current heats up the striker wire only when the necessary voltage is present and when the necessary current flows. For heating up times of less than 1 ms we calculate the heating up as an adiabatic process. The currents along the melting element and the parallel striker wire are in inverse proportion to their resistances. The voltage u_{ME} and the resistance of the striker wire define the current i_{SW}. With R_{SW} as cold value resistance of the striker wire, in the first moment after the arcing process created the arc voltage $u_{ME} = N*U_E$, the current i_{SW} is flowing along the striker wire.

$$i_{SW} = N*U_E / R_{SW} \tag{3}$$

The current i_{SW} heats up the wire. The resistance R_{SW} of the wire rises with rising temperature, the current i_{SW} decreases. The length and the cross section Q_{SW} of the striker wire deliver the resistance and the ratio of the currents along the striker wire and along the melting element. The melting time of the wire and therefore the duration of the pause in the voltage rise can be determined by the current and the melting integral $(i^2t)_{SW}$ of the homogenous wire. The melting integral is

$$(i^2t)_{SW} = K_{SW}*(Q_{SW})^2 \tag{4}$$

The melting value K_{SW} for adiabatic heating is easy to determine. For silver material e.g. the melting value for adiabatic heating is K_{Ag} = 73 000 A^2s/mm^4 [1]. The striker wire changes into liquid before the wire is constricted. The resistance rises until the wire disrupts. We assume the resistance of the wire to be constant from low temperatures up to the melting temperature. Additionally we assume 85% of the melting integral to be reached when the wire has reached the melting temperature.

4 THE PAUSE IN THE VOLTAGE RISE

When we know how the resistance of the striker wire depends on the temperature, we can calculate the momentaneous values i_{SW} of the current and the $(i^2t)_{SW}$-value for the same moment. If we aggree to have a good approximation, we assume the resistance R_{SW} of the striker wire to be constant up to the melting temperature. Then the current along the striker wire is constant too. Formulas (3) and (4) allow to calculate the time t_{SW} to reach 85% of the melting integral of the striker wire.

$$\begin{aligned} t_{SW} &= 0.85*K_{SW}*(Q_{SW})^2 / (i_{SW})^2 \\ &= 0.85*K_{SW}*(Q_{SW})^2 *(R_{SW})^2 / (N*U_E)^2 \end{aligned} \tag{5}$$

We replace the resistance R_{SW} of the striker wire by its length L_{SW}, its cross section Q_{SW} and its resistivity ρ and receive the expression $R_{SW} = \rho*L_{SW}/Q_{SW}$. We insert this in (5) and get the pause time t_{SW} in the voltage rise.

$$t_{SW} = 0.85*K_{SW} * \rho^2 * (L_{SW})^2 / (N*U_E)^2 \tag{6}$$

K_{SW} and ρ are material values. A big resistivity ρ means a small melting value K_{SW}. A long striker wire results in a large pause, a short striker wire in a short pause in the rise of the arcing voltage across the melting element.
Because the ohmic resistance of the striker wire rises with rising heating time, the current along the wire will decrease. Therefore the time to reach the melting temperature of the wire will rise too. Formula (5) delivers a value t_{SW} something smaller than the experiment.

5 THE DISRUPTION OF THE STRIKER WIRE

The striker wire disrupts at the beginning of the arcing process in the melting element. When striker wire has changed into liquid and the current has built up the melting integral of the wire, the wire disrupts. When there is only the wire in a RL-circuit, the inductivity L delivers the energy to disrupt the wire. The current density in the wire and the cross section of the wire define the number N_{SW} of the interruptions in the wire. The arcing voltage along the melting element defines the voltage along the striker wire. When there should be any current flowing along thr striker wire, a voltage value of $N_{SW}*U_E$ must exist.
The disruption of homogenous wires and strips have already been described in the literature. Jan Nasilowski reports the average distance between two disruptions caused by a heavy short circuit current in the wire. The formula has been found experimentally [3].

$$A = 2.08*D + 0.555 \tag{7}$$

Distance A and diameter are measured in mm. The distance A is a characteristic of the single wire. When we have several parallel wires, the cross section increases. If the test current density remains constant, the distance will remain constant too. With the length L_D of the wire and the average distance A of the disruptions, we find the number $N_D = L_D / A$ of the created arcs. Is there sufficient current flowing across the arcs in the melting element, the melting element creates the voltage $N*U_E$. When the heating up of the striker wire takes over all the current, the arcing process in the melting element ends. The voltage $N*U_E$ disappears. The resistance of the disruptions in the melting element rises, the dielectric strength u_{IS} rises only minimal.
Formula (7) delivers also the number N_{ME} of the disruptions of the striker wire. When the wire disrupts, it creates a voltage until a current beginns to flow along the melting element.
(1) defines the maximum voltage $u_{SW} = N_{SW} * U_E$, that arises, when the striker wire disrupts. With the melting element parallel to the striker wire, the voltage along the striker wire rises up to the value u_{ME}. In the moment the

current along the melting element creats arcing, the voltage decreases to the value $N_{ME}*U_E$. At the same time the current along the striker wire decreases.

6 EXPERIMENTAL RESULTS

The fuse voltage and current were measured all 30 µs. The resistance was calculated for each measurement. All values were plotted in the diagrams 1 to 6. In the pause time the resistance is almost constant.

6.1 TEST HH98461

Before the constriction disrupts, the resistance oft the constriction has grown so much that the current creates a voltage drop equal to the voltage $U_E = 55$ V. According to (1) a row of 78 single arcs in line deliver the voltage value $u_{ME} = 78*U_E = 4290$ V. The test confirms the calculated value. This voltage is big enough to create a current along the striker wire. The known values of the melting element and the striker wire of Konstantan lead to both the resistance values and the melting integrals. The resistance of the four parallel melting elements is $R_X \approx 45$ mΩ cold value, the resistance of the striker wire is $R_{SW} \approx 9.3$ Ω cold value. We did not measure the values before the test. When the constrictions disrupt, we measure the current $i_M = 1088$ A. The arcs in the melting element and the parallel striker wire result in a resistance $R_M = 4290/1088$ Ω $= 3.94$ Ω (diagram 3).
The striker wire takes over a part of the measured current. When the resistance of the striker wire is 9.3 Ω, the resistance R_{ME} of the interrupted melting element must have the value 6.8 Ω. Along the wire the current is $1088*6.8/16$ A = 460 A, along the melting element the current is $1088*9.3/16$ A = 630 A. In this breaking test the striker wire takes over 42% of the total current i_M. This means a remarkable influence of the striker wire on the arcing process of the melting element. In Diagram 2 we see, that the current rises for another 400 µs. Hence the current along the wire and along the melting element rise too. When we assume the resistance along the melting element and the striker wire to be constant, the voltage along the fuse link rises.
With the melting constant $K_{SW} = 16400$ A²s/mm⁴ for Konstantan formula (4) delivers the melting integral of the wire $(i^2t)_{SW} = K_{SW} * (Q_{SW})^2 = 39.5$ A²s. According to formula (6) the influence of the striker wire to the pause in the voltage rise is $t_{SW} = 1.6*10^{-4}$ s = 160 µs. The oscillogram delivers the value 200 µs.

6.2 TEST HH98668

A wire melting element with 5 short constrictions creates the voltage $u_{ME} = 5*U_E = 275$ V at the beginning of the arcing process. If each constriction is a homogenous wire, we had to consider formula (7). The wire diameter $D \approx 0.18$ mm delivers the average distance $A \approx 0.93$ mm between the disruptions. The length $s \approx 18$ mm of the constriction yield the number $N_S = s/A = 18/0.93 = 19$ disruptions. Five of these constrictions in line deliver $N_{ME} = 5*19 = 95$ single arcs in line and the arcing voltage $u_{ME} = 95*U_E = 5225$ V. The test confirms the calculated value (diagram 4). The resistance of the 3 parallel wires of the melting element is calculated to be $R_{ME} \approx 80$ mΩ cold value, the resistance of the striker wire is $R_{SW} \approx 7$ Ω cold value.We did not measure the values before the test. The arcing voltage u_{ME} and the measured melting current $i_M = 700$ A deliver the resistance value $R_M = 5225\text{V} / 700\text{A} = 7.5$ Ω. The current along the striker wire is $i_{SW} = 5225$ V / 7.5 Ω = 700 A. Thus the striker wire needs the whole current in the fuse. There is no current left to keep the arcs burning. The arcs cool down, their resistance rise. The dielectric strength of the interuptions is only minimal above the value $N_{ME}*U_E$..
Again formula (6) delivers the pause time t_{SW} in the voltage rise: $t_{SW} = 0.85*16400*(0.5)^2 * (0.6)^2 / (95*55)^2$ s $= 4.6*10^{-5}$ s = 46 µs. The test delivers about 50 µs (diagram 4, before the first maximum).
After the melting integral of the striker wire has been reached, the wire disrupts. The voltage rises fastly. The dielectric strength of the interuptions in the melting element does not withstand the voltage. The interruptions break. The current shifts from the striker wire to the melting element. The arcing process with its electrode effect voltage $u_{ME} = N_{ME}*U_E = 95*55$ V = 5225 V starts once more.

7 CONCLUSIONS

In melting elements for small rated currents a remarkable part of the melting current is shifted to the parallel striker wire. This creates a pause in the arcing process along the melting element. A short striker wire takes over the whole current and interrupts the arcing process along the melting element. In order not to disturb the arcing process, the minimum length of the striker wire must create a voltage drop equal to the arc voltage u_{ME} . Formula (6) shows, that we have a short pause in the voltage rise. When we calculate the arc voltage along a fuse element after disruption of the constrictions, we must regard the resistance of the parallel striker wire.

8 REFERENCES

[1] H.G.Rex: Calculations of adiabatic processes, ICEFA papers 1984, Trondheim, N

[2] H.G.Rex: The arcing process in LV-HRC-fuse links as a combination of two simple processes, SAP papers 1997, Lodz, P

[3] J.Nasilowski: Chain of arcs as determining factor in electrical explosion of wires, ICEFA papers 1976, Liverpool, UK

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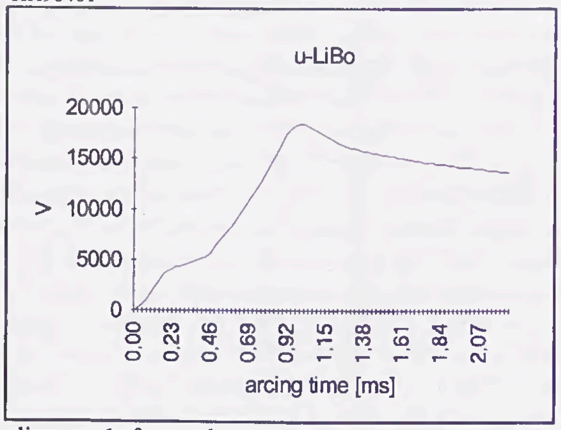

diagram 1: fuse voltage

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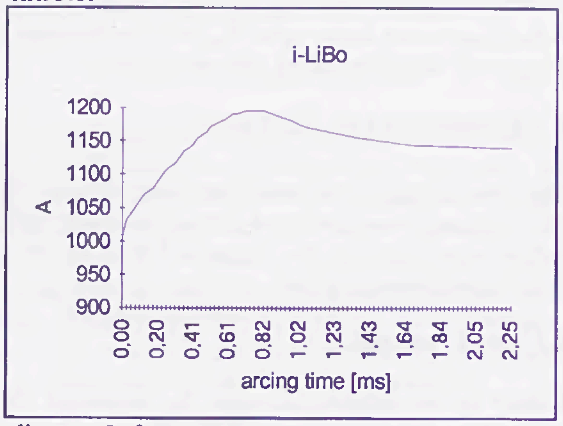

diagram 2: fuse current

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melting element: Ag ; 4 strips parallel
1.8 mm width ; 0.03 mm thick ; 550 mm long
constrictions: round holes ; 1.0 mm diameter
distances : 7.0 mm; 78 rows of constrictions per strip
cross sections: $Q_E = 0.096$ mm² ; $Q_B = 0.216$ mm²

striker wire: Konstantan
0.25 mm diameter; 930 mm long
$Q_{SW} = 0.049$ mm² ; $R_{SW} = 9.5\ \Omega$

Test:
50 Hz/ 10.5 KV/ 1020 A/ cos $\varphi = 0.07$ / $\psi = 10°$
melting time: 3.4 ms ; melting integral: 869 A²s
melting current: 1000 A

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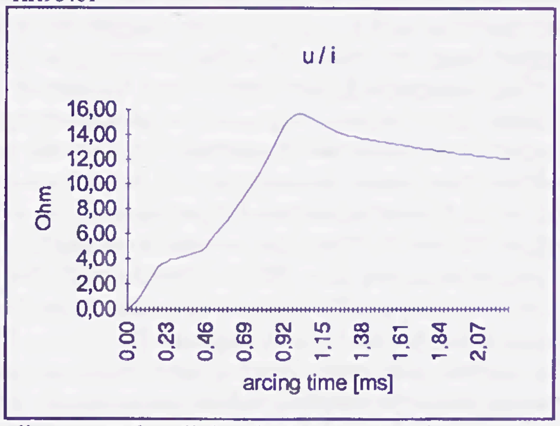

diagram 3: fuse link calculated as a resistance

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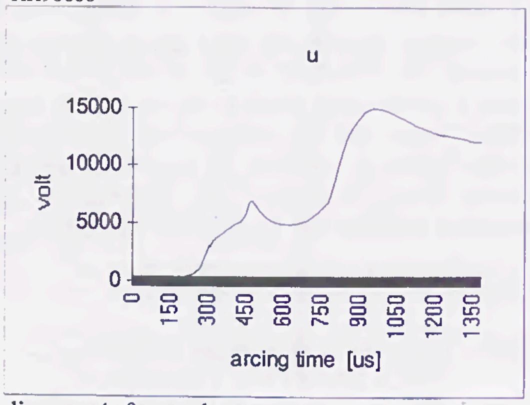

diagram 4: fuse voltage

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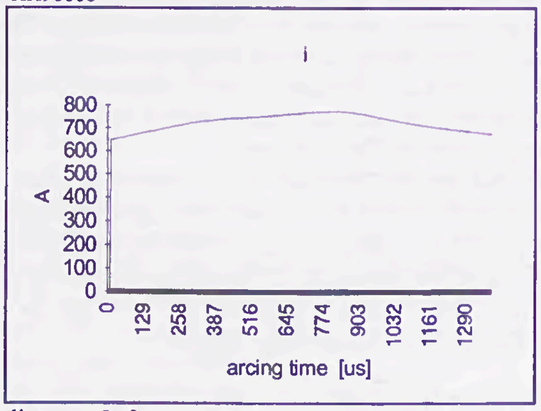

diagram 5: fuse current

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wire melting element:
Ag ; 3 wires parallel, with constrictions
wire: 0.33 mm diameter; 330 mm long
constrictions: wire 0.18 mm diameter
18 mm long; distances : 65 mm;
5 rows of constritions per wire
cross sections: $Q_E \approx 0.078$ mm² ; $Q_D \approx 0.256$ mm²
$R_{ME} \approx 80$ mΩ cold

striker wire: Konstantan
0.25 mm diameter; 600 mm long
$Q_{SW} = 0.049$ mm² ; $R_{SW} \approx 7$ Ω cold

Test: 50 Hz/ 6.3 KV/ 694 A/ cos φ = 0.07
melting time: 3.9 ms ; melting integral: 466 A²s
melting current: 700 A

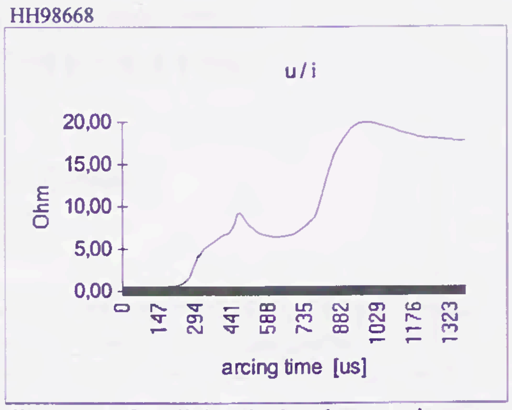

diagram 6: fuse link calculated as a resistance