The dielectric reignition of electric fuses at small overcurrents

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Abstract:

The dielectric recovery of a fuse model is investigated by a synthetic test circuit. The influences of the melting time and of the arc energy on the dielectric recovery strength are represented. The used fuse element is a silver band with a single notch. The electric fuses are stressed with small overcurrents. Simple models for these conditions are represented for the calculation of the arc period and the dielectric recovery.

List of symbols

A_a	arc cross-section	[mm^2]
b	arc channel width	[mm]
C	capacitance	[μF]
e	electric field strength	[V/mm]
$e_{D,0}$	dielectric strength of the reference experiment	[V/mm]
e_D	dielectric strength	[V/mm]
h	arc channel thickness	[mm]
i	current	[A]
l_c	arc channel length	[mm]
l_f	fulgurite length	[mm]
R1,R2	resistance	[Ω]
T	average plasma temperature	[K]
t_a	arcing time	[ms]
t_m	melting time	[s]
t_{cz}	time after current zero	[ms]
u1	load voltage	[V]
U2	test voltage	[V]
u_{ac}	electrode drop	[V]
u_a	arc voltage	[V]
W_a	arc energy	[Ws]
α, β	approximation constants	[-]
ε	emission coefficient	[-]
κ	specific electric conductivity	[1/Ωmm]
σ	Stefan- Boltzmann-constant	[W/mm^2K^4]

1 Introduction

The melting period and the arcing period of electric fuses have often been subjects of experimental investigations as well as theoretic research. Accordingly a great diversity of calculation models exists for the description of these processes. In comparison with those the process of the recovery is not researched very intensively /1 - 6/. The processes which lead to a reignition of the arc after current zero are very complex. Referring to reignition one usually takes into account two extreme cases the thermal and the dielectric reignition. The residual plasma has an electric conductivity after current zero by the thermal inertia of the arc plasma. Therefore, a post arc current exists due to the transient voltage. A thermal reignition of the arc occurs if the power input to the residual plasma by the post arc current is higher than the power loss caused by the cooling . After current zero the former arc channel between the electrodes has a smaller dielectric strength in comparison with a cold gas channel because of the high gas temperature. This high temperature decreases slowly with time. A dielectric reignition will occur if the transient voltage is higher than the momentary breakdown voltage accross the electrodes.

For the accurate knowledge about the reignition process of electric fuses different investigations are necessary for both thermal and dielectric reignition. The aim of our research is the investigation the dielectric recovery of a fuse filled with quartz sand. With the knowledge of the dielectric recovery behaviour of the fuse one can obtain some outcomings of the influence of the thermal processes within the whole recovery.

2 Experimental investigations

2.1 Experimental arrangement

The synthetic test circuit for the measurement of the dielectric recovery strength of electric fuses is shown in **figure 1.**

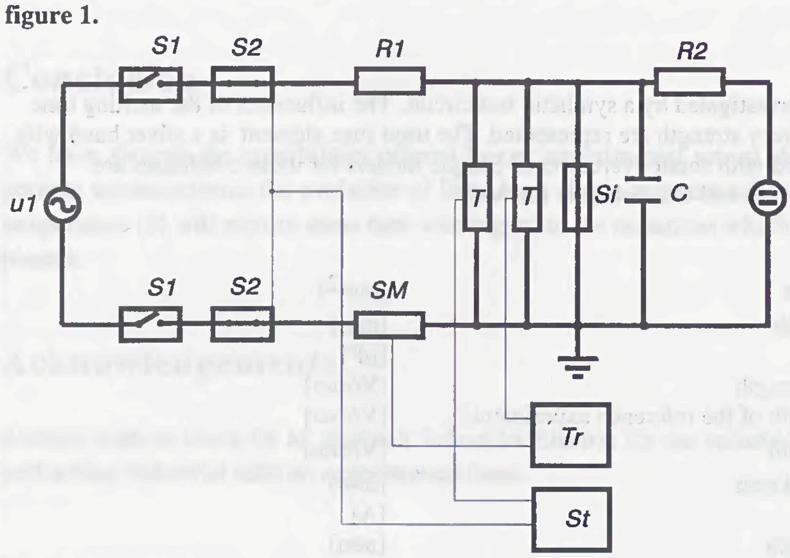

Figure 1: Synthetic test circuit

u1 - load voltage, T - voltage divider, U2 - test voltage, SM - current measuring device, R1, R2 - resistance, St - control unit, C - capacitance, Tr - digital oscilloscope, Si - fuse model, S1, S2 - vacuum switch

The device operates according to a method published by OZAKI /7/ and is qualified for recording of a complet dielectric recovery strength charateristic during one test. At first the electric fuse is loaded with a voltage u1 (up to 5 040 V) and a current up to 200 Amps. The beginning of the arcing period is recorded by a threshold voltage of about 30 volts. The arcing period can be interrupted after 45 ms (switching delay of S2) in every half-cycle. The arrangement shown in /6/ is used for short arcing times. After the interruption by the load voltage u1 and the charging of the capacitance c the test object is loaded with the test voltage U2. A dielectric reignition will take place if the charging voltage of the capacitance is higher than the breakdown voltage of the former arc channel. The capacitance is recharged after the breakdown. These processes repeat themselves until the breakdown voltage of the former arc channel is higher than the test voltage U2. The energy input and the rate of rise of the test voltage are controlled by U2,R2 and C in which the energy input after current zero has to be much smaller than the energy content of the residual plasma column. As an example **figure 2** shows the intermittent voltage slope after current zero.

The connection of the voltage maxima gives the dielectric recovery strength characteristic for the investigated fuse element. For a successful application of the measuring method for the investigation of the dielectric breakdowns it is necessary that the residual current of the fuse is much smaller than the test current i2. On the other hand the value of the test current i2 is limited by the requirement of a minimal energy input after current zero. In consequence it is difficult to use the measuring method with a low electric resistance of the fuse after current zero. This can be the case using copper fuse elements or if the fulgurites are rather short. Results of corresponding investigations will be published later.

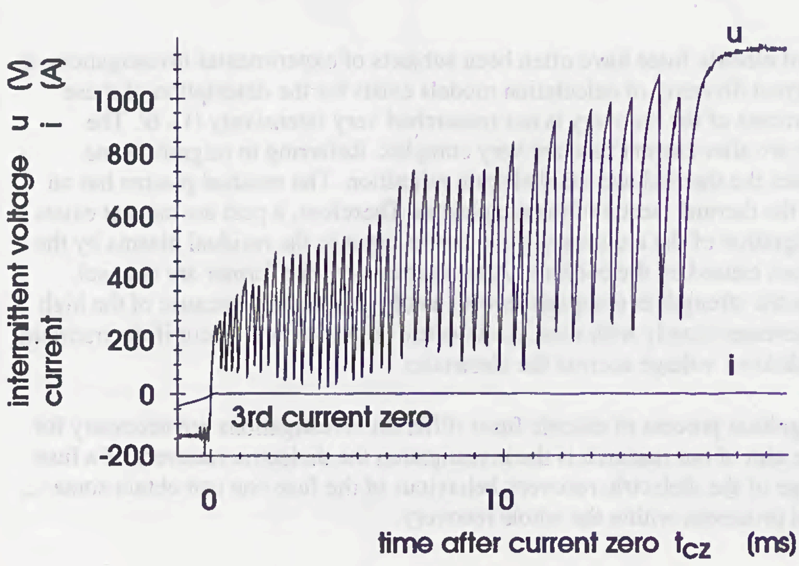

Figure 2: Dielectric breakdown voltage after current zero

parameters:
load voltage u1 = 500 V, test voltage U2 = 1200 V, load current i1 = 27,1 A, test current I1 = 100 mA, capacitance C = 5 nF, melting time t_m = 103 s, arc energy W_a = 26 Ws; fulgurite length l_f = 8 mm

2.2 Test conditions

A coaxial fuse modell is used as a test object whereby a fast exchange of the fuse element and the quartz sand is possible. Silver is used as the fuse element material. The thickness of the fuse element is 0,07mm and its width is 1 mm. The notches of the fuse element are produced by a perforator. The cross section of the constriction is 0,5*0,07 mm^2. The particle size distribution and the composition of the used quartz sand is shown in **table 1.** The quartz sand density amounts to 1,68 g/cm^3. **Table 2** shows the variation region of the test parameters.

Table 1: composition and particle-size distribution

composition substance	particle-size distribution		
	portion %	grainz size mm	portion %
SiO2	> 98	0,5	0,4
Fe_2O_3	< 0,015	0,315	8,3
Al_2O_3+TiO_2	< 0,3	0,2	57,2
CaO+MgO	< 0,2	0,1	33,7
Na_2+K_2O	< 0,1	0,063	0,3

Table 2: test parameter

parameter	range
load voltageu1	500 - 5 040 V
test voltage U2	600 - 7 000 V
load current i1	21 - 200 A
test current I2	100 - 200 mA
capacitance c	0,5 - 50 nF
melting time t_s	- 2 000 s
fulgurite length l_{SR}	4 - 80 mm
arcing time t_{LB}	5 - 300 ms

2.3 Results

The reignition of electric fuses is influenced by the energy input during the melting time as well as the arc energy as already shown in /2,3/. The energy absorption during the prearcing time and the arcing time determines not only the geometry of the fulgurite but also the physical and electrical properties of the gas between the burned back ends of the fuse element. For comparing different measurments the measured breakdown voltage is divided by the gap length between the two endes of the fuse element l_c. The obtained dielectric strength e_D is used as a criterion for the dielectric recovery. The influence of melting time as well as of arc energy on the dielectric strength is to be seen in **figure 3.**

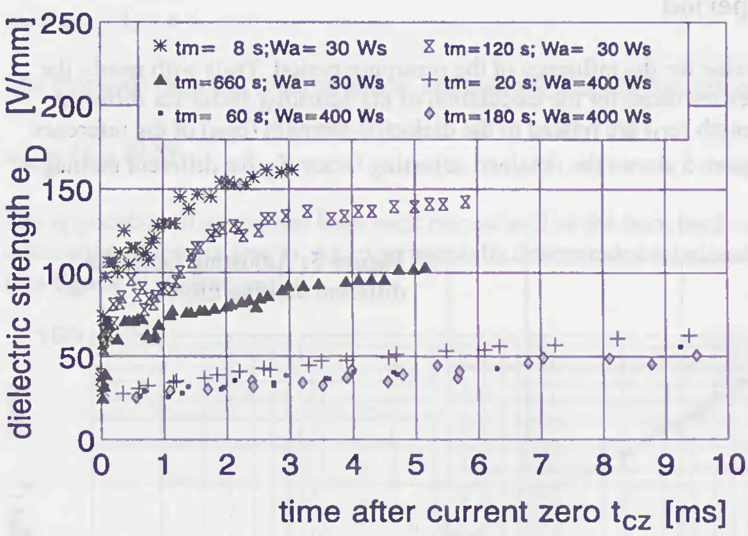

Figure 3: Dielectric strength versus the time after current zero

parameters:
arc energy W_a, melting time t_m

Smaller melting times as well as a small arc energy lead to a steeper course of dielectric strength as function of time. The reason for that is the heating of the quartz sand during the melting time as well as the arcing time, which leads to a less cooling of the residual plasma.

3 Modelling of the recovery strength process

The selection of a reference test is useful to develop an empiric model for the calculation of the reignition process. This curve of the dielectric strength e_{D0} (**see figure 4**) corresponds to a mean value of arc energy (W_a = 444 Ws) as well as of melting time (t_m = 88 s).

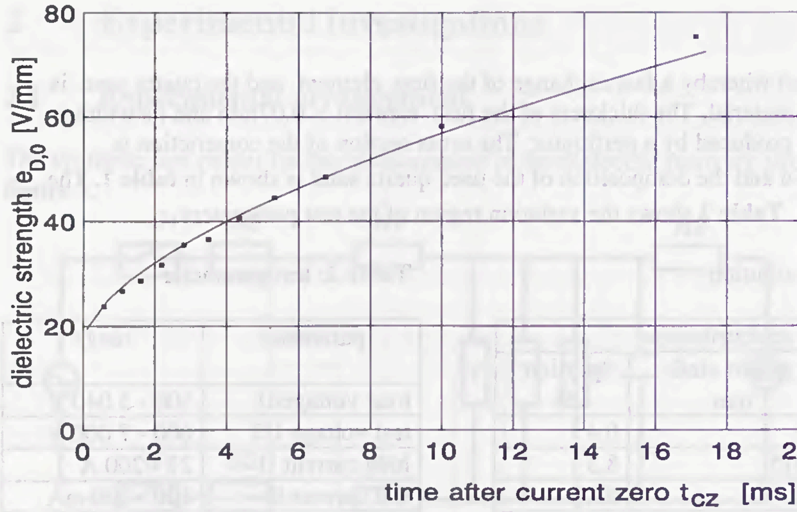

Figure 4: Dielectric strength of the reference experiment versus the time after current zero

The reference test is approximated by:

$$e_{D0} = 17 + 10 * t_{cz}^{0,6} \tag{1}$$

The values of the numbers in the equations (1) - (7), (11) and (13) are only valid using the units of the 'List of symbols'. To take into consideration the different influence of the melting and arcing period adjusting factors f_{tm} respectively f_{Wa} are used as shown in the following equation:

$$e_D = e_{D0} * f_{tm} * f_{Wa} \tag{2}$$

with f_{tm} - adjusting factor for different melting times

and f_{Wa} - adjusting factor for different arc energies

3.1 Consideration of the melting period

The melting time is used as the characteristic value for the influence of the prearcing period. Tests with nearly the same arc energy but with different melting times are taken for the calculation of the adjusting factor for different melting times f_{tm}. The measured dielectric strength (e_D) are related to the dielectric strength (e_{D0}) of the reference test at the time t_{cz} = 1 ms after current zero. **Figure 5** shows the obtained adjusting factor f_{ts} for different melting times.

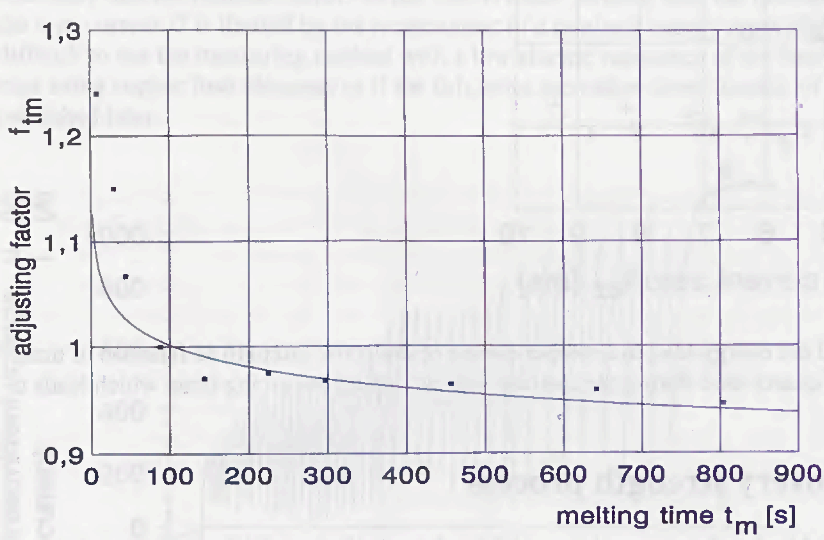

Figure 5: Adjusting factor for different melting times

The characteristic can be described with:

$$f_{tm} = 1,15 * t_m^{-0,03} \tag{3}$$

3.2 Consideration of the arcing period

In order to take different arc energies into calculation the values of the dielectric strength e_D obtained with different arc energies but the melting time of the reference test are compared. **Figure 6** shows the obtained adjusting factor f_{Wa} for different arc energies.

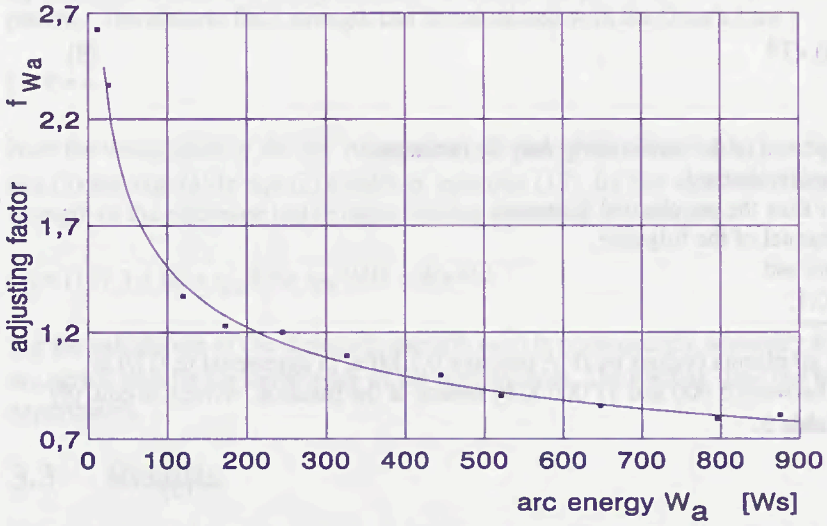

Figure 6: Adjusting factor for different arc energies

The approximation is made using:

$$f_{Wa} = 6 * W_a^{-0,3} \tag{4}$$

The arc energy can be calculated by the correlation of the electrical network and of the arc voltage. The arc voltage is

$$u_a = u_{ac} + l_c * e \tag{5}$$

The electrode drop u_{ac} (sum of anode- and cathode drop) is determined by GNANALINGAM /8/

$$u_{ac} = 15 + i^{0,39} \tag{6}$$

The application of a constant burn back rate as well as the burn back model of DAALDER /9/ are not suitable for the calculation of the arc length. An experimentally determinded relationship between the arc length and the arc energy **(see figure 7)** is more useful.

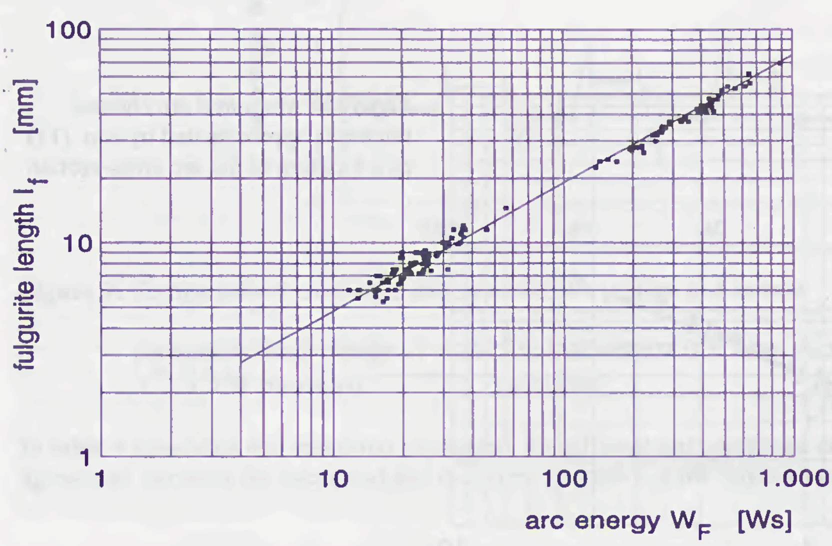

Figure 7: Measured fulgurite length approximated by equ. (7) as a function of the arc energy

The approximation results in

$$l_f = 1,2 * W_a^{0,6} \tag{7}$$

To calculate the electric field strength e of a wall- stabilizied arc a model by HUANG /10/ is used. It starts from following energy balance:

$$i^2 * l_c / (\kappa * b * h) = \varepsilon * \sigma * l_c * 2 * (b + h) * T^4 \tag{8}$$

It is supposed, that
- the whole arc energy is transported to the surrounding only by radiation,
- the arc is quasi - stationary and isothermal,
- the arc length is much higher than the arc channel diameter,
- the arc occupies the whole channel of the fulgurite,
- the arc plasma is an air plasma and
- the emission coefficient ε is 0,1.

The spezific electric conductivity of an air plasma (values by /11/; pressure 0,1 MPa, in agreement to /12/) is approximated in the temperature range between 5 000 and 17 000 K by means of the function, written in equ. (9) using the values for α and β shown in **table 3**.

$$\kappa = \beta * T^{\alpha} \tag{9}$$

Table 3: approximation values

T	α	β
up to 9 000 K	6	$3 * 10^{-24}$
9 000 - 12 200 K	4	$2,5 * 10^{-16}$
above 12 200 K	1,5	$4 * 10^{-6}$

To use equation (8) the size of the arc channel must be known. The measured channel cross sections ascertained by microscopic investigations of fulgurite cross sections are in accordance with the calculated results using equation (10) by GNANALINGAM /8/

$$dA_a/dt = (k_0 + (k_m - k_0)) * (1 - \exp(-t_a/\tau)) * e * i / W_F \tag{10}$$

with
$k_0 = 0,08$,
$k_m = 0,63$,
$W_F = 3,8$ Ws/mm³,
and $\tau = 10$ ms .

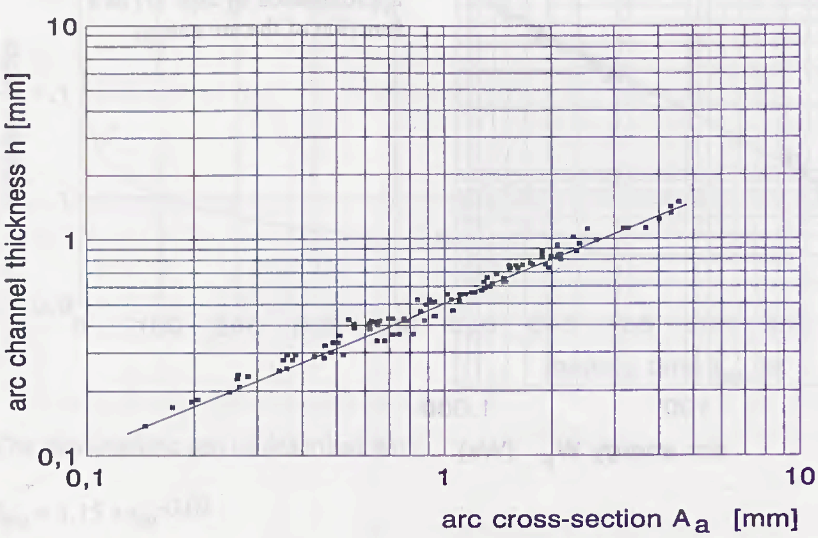

Figure 8: Measured arc channel thickness approximated by equ. (11) as a function of the arc cross-section

Independently of the load of the fuse element the evaluation of the measurements results in a relation between the fulgurite channel cross-section and the fulgurite channel thickness (**see figure 8**) corresponding to

$$h = 0{,}5 * A_a^{0{,}675} \tag{11}$$

By means of the equations (8), (9), (10) and (11) is it possible to determine the spezific electric conductivity of the plasma . The electric field strength can be calculated with the Ohm´s Law :

$$j = \kappa * e \tag{12}$$

Now the designation of the arc voltage (equ. 5) and of the adjusting factors f_{Wa} equ.(4) is possible. The insertion of equ.(3) and equ.(4) in equ.(2) results in equation (13). By this equation it is possible to transfer the dielectric strength of the reference test to other melting times and arc energies.

$$e_D = (117{,}3 + 69 * t_{cz}^{0{,}6}) * t_m^{-0{,}03} * W_a^{-0{,}3} \tag{13}$$

For the calculation of the dielectric strength e_D it is consequently necessary to know the energy absorption during the arc period besides the knowledge of the melting time. The melting time can be determined by calculations /13/ or by experiments.

3.3 Results

The arc period of electric fuses at small over currents lasts several half-waves. The arc period is interrupted after each current zero by the recovery process. In this phase it is decided whether the current will be cut off or the reignition of the arc occurs. The dielectric strength characteristic of the gap must be calculeted by a mathematic simulation after each arc half-wave corresponding to the energy input during the whole arc period. A reignition will take place if the transient voltage reaches the breakdown voltage of the gap. To compare the measured and the calculated current and voltage curves it is necessary to take the ignition time of the arc from the measurement, because it is difficult to calculate the ignition time of the arc within a half-wave for long melting times. **Figure 9** demonstrates an example of the calculation of the arc period for a single notched fuse element.

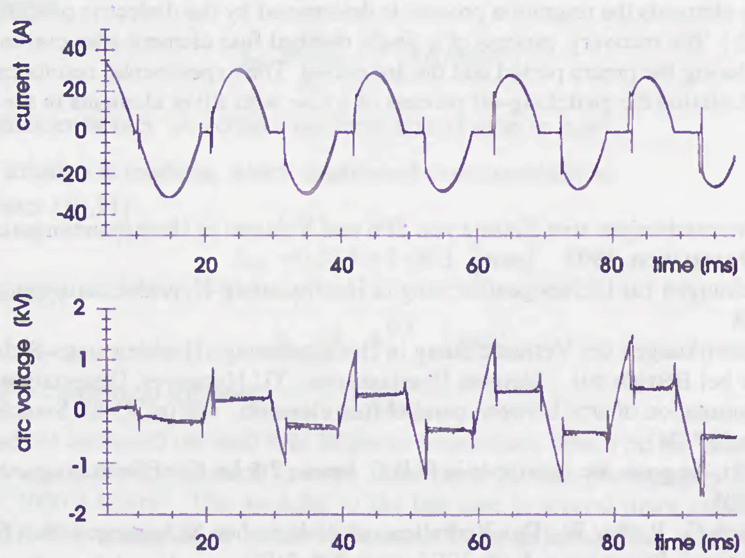

Figure 9: Comparison of calculated and measured arc voltage and current

parameters: load voltage u1 = 1413 V, load current i1 = 24 A, melting time t_m = 804 s

measured, calculated

In **table 4** calculated and measured parameters for different test conditions are shown. There is a rather good agreement between the calculated and measured geometry of the fulgurite as well as of the electric parameters.

Table 4: Calculations with different test conditions

parameter	half wave									
	1.		2.		5.		7.		9.	
	cal.	meas.	cal.	meas.	cal.	meas.	cal.	meas.	cal.	meas.
u1=500 V, i1=23 A, t_m=310 s	fuse element length 50 mm									
arc energy [Ws]	10,54	9,3	30,6	29,86						
fulgurite length [mm]	4,9	-	9,36	10						
arc channel thickness [mm]	0,18	-	0,3	0,35						
arc channel width [mm]	1,22	-	1,56	1,46						
max. mean temperature [K]	18629	-	14168	-						
breakdown voltage [V]	437	512	-	-						
u1=1413 V, i1=24,5 A, t_m=569 s	fuse element length 100 mm									
arc energy [Ws]	1,58	1,69	27,3	26,3	148	168,4	249	275,4	361,8	386,2
fulgurite length [mm]	1,5	-	8,7	-	24,1	-	32,9	-	41,1	41,5
arc channel thickness [mm]	0,1	-	0,3	-	0,65	-	0,8	-	0,92	0,84
arc channel width [mm]	0,96	-	1,59	-	2,27	-	2,5	-	2,68	2,5
max. mean temperature [K]	17654	-	15463	-	10937	-	10208	-	9744	-
breakdown voltage [V]	93	360	567	520	1272	1160	1343	1400	-	-
u1=2773 V, i1=26 A, t_m=78 s	fuse element length 100 mm									
arc energy [Ws]	3,7	1,8	37,9	30,7	205	199	357,5	350,4	535,9	521
fulgurite length [mm]	2,6	-	10,6	-	29,2	-	40,8	-	52,8	54
arc channel thickness [mm]	0,13	-	0,36	-	0,72	-	0,89	-	1,04	1,12
arc channel width [mm]	1,04	-	1,67	-	2,38	-	2,65	-	2,84	2,75
max. mean temperature [K]	18995	-	15422	-	11031	-	10311	-	9840	-
breakdown voltage [V]	233	280	525,8	360	1042	1160	1210	1280	-	-

Summary

Based on the good agreement between the calculation and experimental measurment the following conclusion can be made. Using silver fuse elements the reignition process is determined by the dielectric process with the given test conditions (see chapter 2.2.). The recovery process of a single notched fuse element after current zero is influenced by the energy absorption during the prearc period and the arc period. The experimental results can be summarized in an empirical model for calculating the switching-off process of a fuse with silver elements in the region of small overcurrents.

Literature

/1/ Brechtken,D.: Untersuchungen zum Einsatz von SF6 und Vakuum in Hochspannungssicherungen; TH Darmstadt, Dissertation, 1993

/2/ Trott,J.: Untersuchungen zur Lichtbogenlöschung in Hochspannng-Hypridsicherungen; TH Darmstadt, Dissertation, 1988

/3/ Stenzel,H.D.: Auswirkungen der Verlustleistung in Hochspannungs-Hochleistungs-Sicherungen auf den Sicherungskörper bei Betrieb mit kleinem Überlaststrom; TU Hannover, Dissertation, 1972

/4/ Wilkins, R.: Commutation of arcs between parallel fuse elements. 6th Int. Conf. Switching arc Phenomena, Lodz, 1989, page 237-241.

/5/ Cwidak, K., Lipski, T.: post- arc resistance in H.B.C. fuses ; 7th Int.Conf.Switching arc Phenomena, Lodz 1993, page 202-205

/6/ Ehrhardt A., Nutsch G., Rother W.: Das Verhalten von elektrischen Sicherungen nach Stromnull; 7th Int.Conf. Switching arc Phenomena, Lodz 1993, page 206-210

/7/ Ozaki, Y.: Study on the dielectric recovery , characteristics of lightning arrester spark- gaps; ETJ of Japan 5 (1960) H. 3/4 page 94-97

/8/ Gnanalingam, S.; Wilkins, R.: Digital simulation of fuse breaking tests; IEE Proc. London 127 (1980) 6. page 434- 440

/9/ Daalder,J.E.,Schreurs,E.F.: Arcing Phenomena in High Voltage Fuses EUT Report83-e-137-Eindhoven (1983)

/10/ Huang, H.: Lichtbögen in Spalten ; TU Braunschweig, Dissertation, 1992

/11/ Johann, H.: Elektrische Schmelzsicherungen für Niederspannung: Vorgänge, Eigenschaften, technischer Einsatz; Berlin : Springer Verlag, 1972

/12/ Boulos, M.I., Fauchais, P., Pfender, E.: Thermal Plasmas Fundamentals and Applications Volume 1; PLENUM PRESS NEW YORK and LONDON, 1994

/13/ Kürschner, H., et al: Calculation of prearcing times using the Finite Element Method, ICEFA-95