ARC IGNITION PROCESS IN SHORT FUSE ELEMENTS

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***Abstract**:* Research on short fuse elements, approx. 1 mm in length, allows for analysis of the disintegration process at the stage of of single elementary gaps in the fuse element. Examinations were performed at a current density of 4...150 kA/mm^2. It was shown that arc voltage at a single gap, during arc ignition, does not exceed 30 V. Higher values observed are a resultant value of arc ignition voltages at a larger number of very short (0,04 .. 0,12 mm) segments of arcs between fragments of the fuse element material, connected in series. These examinations confirm the two-stage character of fuse element disintegration. The first stage, with a considerably shorter module of disintegration is caused by an electro-thermo-hydro-dynamic mechanism. Next, longer channels of electrical arc discharge are formed after neighbouring segments of elementary short arcs from the first stage of fuse element disintegration join together one by one. The average module of fuse element disintegration becomes longer, while the unitary voltage of a segment of the fuse element's current circuit decreases. Results of examinations allow us to modify some earlier hypotheses on fuse element disintegtration and contribute new numerical data characterising these phenomena.

Keywords: electric fuse, arc ignition voltage

1. Introduction

The active area of operation of a fuse includes current values above fusing current, which corresponds to the current value at which curcuit – fuse element continuity is lost. The fuse element is most often made from conductive materials: copper or silver. Many research works were made to explain the mechanism of fuse element disintegration at current flow above fusing current value. It was noted [1, 2,] that the mechanism of fuse element disintegration depends mainly on the intensity of the energy accumulation process, i.e. the power P_F of energy transformations in the fuse element's environment. The power P_F depends on the intensity of the current I_F flowing through the fuse element, and on the physical properties and dimensions of the fuse element. To determine the properties of fuse element disintegration, we most often use the parameter of current density j_F of the fuse element. With high dynamics of current density increase in the fuse element, dynamic energy transformations take place in the fuse element material. Phase transformations, as well as movements of the fuse element material can take place, leading to deformation of its original shape. This forces a dynamic change of the elastic thermal and electromagnetic field of the circuit segment. These are effects mutually dependent in the area and they can lead to instability of particular states. A characteristic symptom of this instability is disintegration of the fuse element.
The droplets disintegration mechanism in the fuse element, taking place at small current overloads has been well examined, while striated and chaotic disintegration mechanism, which take place at large overcurrents, have been extensively described in literature, but are not yet been fully known.
In recent times, two large state of research works have been published, treating this issue. Wolny [3] cites many results from his own and other scientists' research, around 300 bibliographic items, explaining the process of current cut-off, including that in fuses. This literature treats mainly effects taking place in the macroscopic scale, e.g. a long fuse element of various short-circuit conditions corresponding to electrical power circuits of AC 50 (60) Hz or DC with typical values of the time constant for short-circuit currents (7,5 ...30 ms). The second research work, by Jakubiuk [4], is a very deep study of the physical effects taking place in a fragment of the current circuit in which there is an extremely high concentration of energy connected with flowing current. In these conditions, the physical segment of the circuit simply explodes.
Table 1 shows conventional current values, marked I_p and I_{SSS}, respectively, in several types of circuits, which correspond to assumed rates of current increase. The I_p current is the value of (RMS) expected short-circuit current, while the I_{SSS} current is the conventional maximum switching current value for a Solid State Switch in a power electronics converter. In classical electric circuits, rates of current increase do not exceed approx. 20 ... 50 A/µs. Physical effects taking place in a disintegrating fuse element in these conditions, are usually assessed on the basis of an analysis of oscillograms of the voltage at the fuse element (usually long) and on the basis of the condition of the fuse element after the current has been cut off.

Prospective short circuit current: I_p- in an AC (*f* - frequency), or DC (*T* - time constant) and I_{SSS} – for Solid-State-Switches (SSS) in power electronic converters (*T/2*-half period time for free oscillations circuits, t_r – SSS switching on time) for the rate of the current *di/dt*

di/dt *[A/[µs]*		0,5	1	2	5	10	20	50	100	200	500	1000
		***I**_p_ [kA]*										
f *[Hz]*	50	1,13	2,26	4,52	11,3	22,6	45,2	113	225			
	60	0,93	1,87	3,74	9,95	18,7	37,4	93,5	187			
T *[ms]*	30	15	30	60								
	15	7,5	15	30	75							
	7,5	3,75	7,5	1`5	37,5	75						
		***I**_SSS_ [kA]*										
T/2*[ms]*	1	0,16	0,32	0,64	1,6	3,2	6,4					
t_r *[µs]*	5	0,0025	0,005	0,01	0,025	0,05	0,1	0,25	0,5	1,0	2,5	5
	1	0,0005	0,001	0,002	0,005	0,01	0,02	0,05	0,1	0,2	0,5	1

Works – dating from 1960-1970, by Lipski [1], Hibner [5], Nasiłowski [2] and other scientists examining X-ray photos of fuse elements after the current was cut off, and by Arai [6], Fansler, Shear [7], and others, who took X-ray pictures of particular phases of fuse element disintegration – are commonly known. The image of the fuse element in the pictures was proof of a particular type of fuse element disintegration. The full mechanism of disintegration during large overcurrents was not, however, assessed. Lipski [8] was the author of the hypothesis, that during the initial phase, the fuse element breaks up into a larger number of segments than can be seen in the final form of the use element, after the current has been cut off. Jakubiuk [4,9,10] gave the theoretical bases for the fuse element's initial and secondary disintegration at high current densities.
Presented below are selected results of examinations during the initial phase of arc ignition in a fuse element, at a high rate of current increase.

2. Research

As was mentioned above, numerous authors examined the characteristics of fuses, which had a (high) ability to limit and cut-off fault currents in a cicuit with a rated voltage U_e, of e.g. 500 V, 3 kV and more. In such conditions, voltage in the fuse reflects the sum of voltages of a dynamically changing number of arcings in the elementary gaps of a long segment of a fuse element.
Fig.1 gives an example of current trace $i_F(t)$ and of the voltage $u_F(t)$ in the fuse element in a circuit with a rated voltage $U_e = 4$ kV DC and with a current increase rate $di_F/dt \approx 5$ A/µs. If we use oscillogram descriptions of voltage at the fuse during current cut-off as criteria, the voltage trace $u_F(t)$ in fig.1 has the following description: line segment 0 - 1 – increase of voltage in the heating fuse element; line segment 1 - 2 – 3 – arc ignition voltage, line segment 3 - 4 – arc voltage. Assessment of the voltage trace $u_F(t)$ in details regarding the arc ignition mechanism in individual gaps in this oscillogram is impossible.

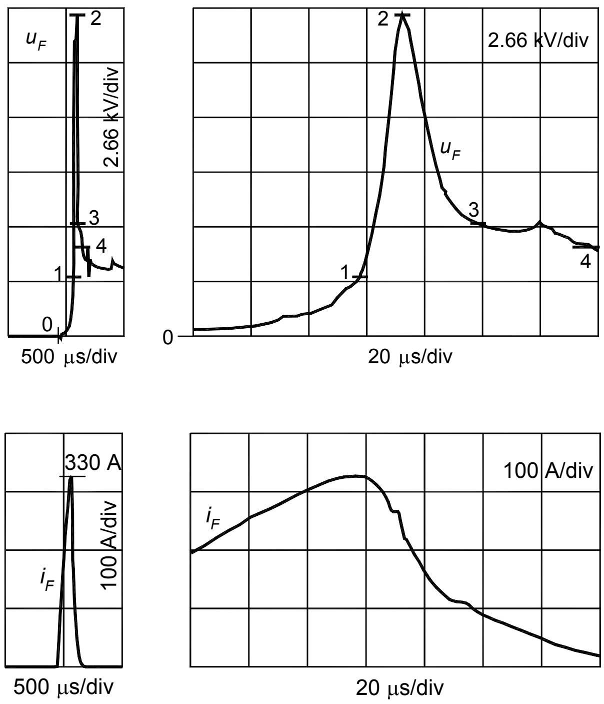

Fig.1: Example of voltage u_F and current i_F
3 kV DC / 3 A fuse in 4 kV, 40 kA / 25 ms short circuit test

E.g. a certain type of fuse, for a voltage $U_e = 4$ kV DC had an element with a total length $l_F \approx 600$ mm, while the length of an elementary segment of conducting plasma λ_e between particular segments of the disintegrating fuse element was $\lambda_e \leq 0{,}15$ mm, and the number n_e of such stochastically distributed and dynamically variable elementary arcing segments exceeded $n_e \geq 500$. The dynamic voltage characteristic $u_F(t)$ of the fuse element conduction during operation results not only from a time-variable balance of the energy that is delivered to the fuse element, and from the conditions (cooling, generally), but is also determined by the "lifetime" dynamics – the appearance and disappearance – of particular segments of short arcs.

If the fuse element length is large, compared to the module of fuse element disintegration in a given sample, then the mechanism of its disintegration does not depend on its length. Therefore, when conducting research on a short fuse element, it is possible to image the physical effects taking place in the elementary fuse element segments with much higher resolution. The dynamics of current changes in electrical circuits (table 1) are relatively small, compared to the dynamics with which particular gaps appear (single µs), therefore, in research on short fuse elements, the rate of increase of the expected short-circuit current should be kept the same as for examinations of long fuse elements. Since the examinations regard a very short interval of time for the appearance of a particular gap in the fuse element, it can be assumed [3,4], that the environment surrounding the fuse element does not have a large influence on the arcing process.

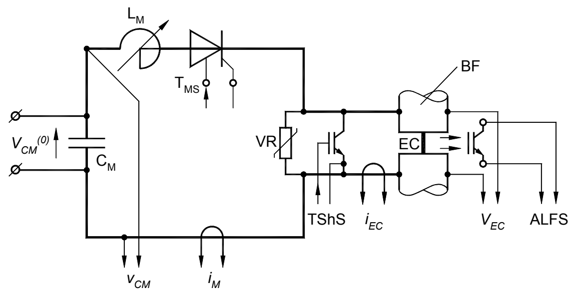

Fig.2. Test circuit diagram. C_M- capacitive source of energy, T_{MS}- thyristor making switch, EC – exploding short fuse element, TShS – transistor shunting switch, VR – ZnO varistor, ALFS – arc light flux sensor, BF – fuse base

Fig.2 shows an equivalent circuit diagram of a test circuit for examining the properties of disintegration of a short fuse element. This is a circuit with a capacitive source of electric energy C_M with adjusted initial voltage $U_{CM}^{(o)}$. Current increase rate in the circuit was set by inductor L_M. The short circuit making switch *TMS* was a thyristor switch. The examined segment of the short fuse element *EC* $l_{EC} = 1$ mm was placed in the fuse base BF. Parallel to the fuse element *EC* , a very fast transistor shunting switch *TShS* was connected, that could be used at any moment t_1, with an accuracy of +/- 1 µs, to force current commutation from the *EC* branch to the *TShS* . Current commutation from *EC* to *TSh*S allowed for a controlled stopping of energy flow to the fuse element *EC*. Assessment of the results of the current flow through the fuse element was possible until the instant t_1. After the the transistor switch *TrSh* was cut off, current i_M commuted to the branch witih the varistor *VR*. In this way, it was possible to shape the transient recovery voltage $u_{EC(TRV)}$ at the fuse element gap.

Fig. 3 shows examples of oscillograms of short fuse element examinations in a test circuit similar to that in Fig .2. Similarly to the oscillograms on the left side of fig. 3, there is no visible any difference in the voltage trace. However, if we stretch the time scale - the oscillograms on the right hand side, we see the differences. Table 2 gives a detailed description of the oscillogram in Fig. 3.b.

An original result of these examinations is documentation of the voltage increase in the fuse element in certain conditions caused by practically a single fuse element disintegration. In this research, details regarding the influences of the fuse element material, current density, current variability or other factors on the arc ignition mechanism during disintegration were not analised.

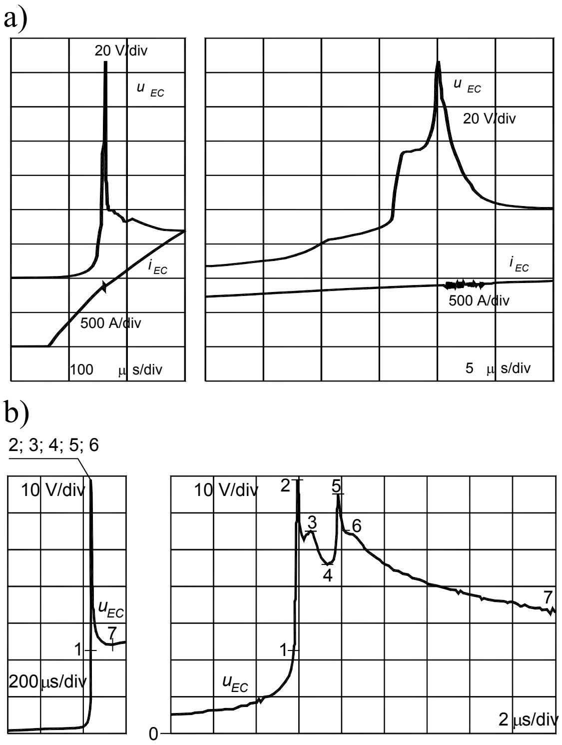

Fig.3. Short fuse elements, $l_F = 1$ mm, test results: a) – Φ 0,1 mm Cu, di/dt ≈ 100 A/µs; b) – 0,1 x 1 mm Ag, di/dt ≈ 25 A/µs – details in tabl.2.

Table.2. A description of physical effects taking place in the current circuit of a fuse element during dynamic current increase i_{EC} (oscillogram in Fig.3b)

Instant/ time interval	Description	Characteristic features	Result in the current circuit EC	Number of gaps n_e
0	current switched on (TMS making)	di_{EC} / dt = 4A/μs dj_{EC} / dt = 40 A/mm^2 μs	increase of temperature, resistance, deformation of shape and cross-section of the EC circuit,	0
0 – 1	voltage increase in the heating fuse element			
1	rapid increase of voltage increase rate	du_{EC} / dt = 450 V/μs	loss of EC circuit continuity – first EC disintegration – a plasma conductivity channel forms	
1 – 2 (0,15 μs)	increase of voltage decrease rate in the EC curcuit	$\Delta u_{EC\,(1-2)}$ = 46 V two (serial) gaps appear	electro-thermo-hydro-dynamic deformation of the EC, appearance of local constrictions of the material, weakening of atomic bonds, increase of internal pressure of the EC matter	2
2	change of voltage increase trend	u_{EC} voltage drops rapidly	as a result of electro-thermo-hydro-dynamic forces, one gap "sticks" back together	1
2 – 3 (0,1 μs)		$\Delta u_{EC\,(2-3)}$ = 20 V; du_{EC} / dt = 200 V/μs		
3		„quasi-oscillatory" variation of voltage	„quasi-oscillatory" character of electro-thermo-hydro-dynamic forces causes the appearance / closure of two neighboring gaps, further deformation of the fuse element material	1 → 2 → 1
3 – 4 (0,45 μs)				
4	rapid increase of voltage	steep increase of voltage $\Delta u_{EC\,(2-3)}$ = 23 V; du_{EC} / dt = 200 V / μs	a „new" gap appears	2
4 – 5 (0,12 μs)				
5 – 6 (0,18 μs)	change of voltage increase trend voltage decreases	u_{EC} voltage drops rapidly $\Delta u_{EC\,(2-3)}$ = 14 V; du_{EC} / dt = 130 V/μs	as a result of electro-thermo-hydro-dynamic forces, one gap "sticks" back together	1
6		instability of voltage decrease tendency	instability of EC conductivity: oscillation of matter between successive gaps (?)	1 → 2 → 1
6 – 7 (≥ 30 μs)	slow decrease of voltage to "quasi-steady" state	arc voltage „stabilizes" $u_{EC\,(7)}$ = 24 V;	the electrode bases of the arc come close to the terminals, "constant" arc cooling conditions	1

On the basis of many measurements, it was noted that elementary increase of voltage at a single gap of the disintegrating Cu or Ag fuse element, with fuse element current density j_{EC} within the examined 4 ... 150 kA / mm^2 interval, was approx. $u_{EC}^{(n)}$ = 20...30 V. On the basis of an analysis of the balance of electrical energy delivered to the examined fuse elements and the given physical properties of the fuse element materials, the amount of exploding matter Δm_e, was calculated and converted to a linear measure of the length of a single elementary gap λ_e in the fuse element material, called metallic plasma, or, more often, an arcing discharge. Results were obtained, indicating that the length of an elementary gap during fuse element disintegration at current densities j_{EC} within the examined 4 .. 150 kA / mm^2 interval and fuse element cross-section area s_{EC} = (0,008 ... 0,1 mm^2) equals λ_e = 0,04 ... 0,12 ... mm.

Fig.4 shows examples of an analysis of phase transformations of the mass m_x of a fuse element EC at successive instants t_x during disintegration of a Cu Φ 0,1 mm l_{EC} = 1 mm fuse element, oscillogram in Fig.3.a. This is a considerably smaller value than the one given by Hibner [5], Nasiłowski [2], Vermij [11] and others. On the basis of the high value of voltage during the initial phase of current cut-off and the number of fuse element gaps observed after current cut-off, the value of arc ignition voltage was given for a single elementary gap – as over 50 ..200 V. This was explained, mistakenly – in the author's opinion – by "overvoltages at the inductance of the short-circuit".

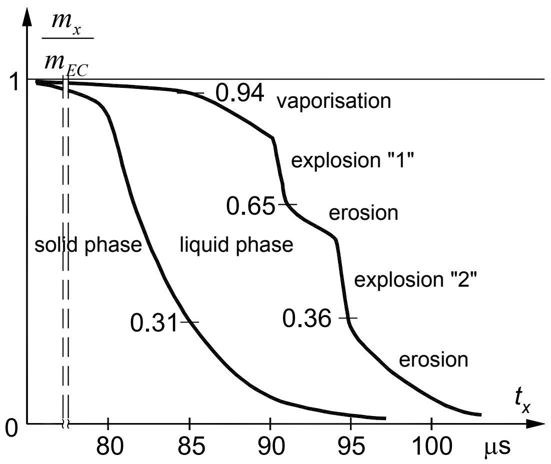

Fig.4 Phase transformation of mass m_x of a fuse element l_F = 1 mm, Φ 0,1 mm Cu at successive instants t_x

Very interesting results, with photos of a disintegrating fuse element, made at mocrosecond time intervals, together with an oscillogram of voltage and current, was presented in [7]. The number of fuse element disintegrations calculated for this oscillogram, corresponding to the instant of maximum voltage in the fuse element, n_a equalled approx. 480, the length of the module of elementary arcing discharges, λ_e = 0,04 mm (at voltage of the n-th gap $\Delta u_{EC}^{(n)}$ = 30 V). Due to the high rate of voltage increase, fuse element disintegration was almost simultaneous along its entire length, which is why such high rates of increase of voltage were observed during the initial phase of disintegration of fuse element EC. Some authors call this chaotic disintegration. In the author's opinion, low resolution of X-ray photography does not allow for observation of such short (regular!) gaps along the fuse element.

The above-mentioned hypothesis of Lipski and the results of the theoretical analysis of the more complex mechanism of fuse element disintegration by Jakubiuk have not – so far - been unequivocally confirmed experimentally.

Selected characteristic results of examinations and calculations regarding the fuse element and test circuit are given in Table 3. Results with the index *R* (***R****eference)* treat calculations made in accordance with principles given in literature, while those with the index *T (****T****est)* treat results obtained by the author in the course of his own research.

It is worth noting, that while analysing the example oscillogram in Fig.3.a, the result of appearing of successive fuse element disintegrations at two successive instants, marked *2* and *5*, and approx. 1,9 µs away from each other, can be also be seen in the form of voltage increase by around 50 V. each. The value of this voltage increase indicates the simultaneous appearance of two microdisintegrations. The appearance, as well as the disappearance of particular gaps is the result of the balance of energy transformations in the fuse element current circuit. Hence, their dynamics are similar – rate of voltage increase during the appearance and during the disappearance of a gap have a similar value.

Table 3. Test (T) and calculation (R) results for the EC tested

Type of EC			Φ 0,1 mm, Cu		0,1 x 1 mm, Ag
$I_{EC(1expl)}$	A	*T*	840	1320	2030
$j_{EC(1expl)}$	kA/mm^2		107	170	22,7
di_{EC} / dt	A/µs		10	43	2,5
dj_{EC} / dt	A/µs.mm^2		1,25	4,3	40
$s^2_{EC}.K$	A^{2}s	*R*	6,08		583
$I^2t_{(0-1expl)}$	A^{2}s	*T*	23,1	22,8	2690
$W_{(0-1expl)}$	Ws		0,33	0,363	1,38
$\Delta W_{(n\ expl)} / n_{expl}$	Ws		0,12 / 2 = 0,06	0,118 / 2 = 0.059	0,202 / 2 = 0,101
λ_e @:s_{EC} = const; h_{gb} = const	mm	*T+R*	0,15	0,145	0,05
s^2_{EC}.K- (square) EC cross section times Mayer's constant; $I^2t_{(0-1expl)}$ parameter value for the time to the first explosion of EC take place; $\Delta W_{(n\ expl)} / n_{expl}$ - only n - explosions energy; λ_e – average length of n-th arcing (disruption); h_{gb} – specific enthalpy of the gaseous phase in boiling temperature					

4. Conclusions

An analysis of short fuse element voltage and current allows for observation of single fuse element disintegrations during high density current flow.

Elementary, very rapid increases of voltage can be observed in the fuse element, with a repetitive (in the sense of measured current densities of approx. 5 ...150 kA/mm^2 at the instant of disintegration) $\Delta u_{EC}^{(n)}$ = 20...30 V values with a rate of increase of a single gap approx. $du_{EC}^{(n)} / dt$ = 30 ... 50 V/µs.

The number of elementary segments n_e of the fuse element with an ignited arc, whose measure is the instantaneous voltage value u_{EC}, is variable in time. Increase of voltage (the number of gaps) is proof of the appearance of further disintegrations while electrical energy is delivered to the fuse element area. Decrease of voltage (the number of gaps) is a result of axial thermo-hydro-elastic forces on the elementary fragments of matter (in solid and/or liquid state) causing short circuiting of neighboring segments. This is a dynamic process, dependent on the parameters of the electrical energy and properties of the fuse element.

The voltage observed at the terminals of the real fuse base is the sum of decreases of voltages on a dynamically changing number of elementary arc segments characteristic for the fuse element material and the flowing current, whose number, in an extreme case, may come down to $n_e = 1$. Then, the arc characteristic determines the voltage in the fuse in a given specific solution of the fuse element cooling conditions.

In the time interval of dynamic changes of voltage, a model of a fuse should be built, based on a circuit diagram consisting of a number (variable in time) n_e of voltage sources with the voltage value of one gap, in conditions similar to those in the research, $\Delta u_{EC}^{(n))}$ = 20 ... 30 V.

It is necessary to perform further research in order to determine the parameters of fuse element disintegration in other conditions: the fuse element material, current density and the material directly adjacent to the exploding fuse element.

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