OVERVOLTAGES PRODUCED BY LV FUSES

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INTRODUCTION The importance of overvoltages in LV networks has increased with the introduction of electronic devices and namely from three standpoints : the damage of semi-conductor elements, faulty functions of electronic devices, interference of communication means both public and private. If we neglect atmospheric overvoltages which, in most cases, do not come into consideration in protected installations according to IEC Publication 71, the LV fuses still remain one of the main sources of the overvoltage .

CASE OF THE FUSE-ELEMENT WITH CONSTANT CROSS-SECTION

We suppose the conductor of the length l and the cross-section s, through which the current I is flowing. Radial heat dissipation can be neglected because it does not overpass 10%. All the heat is dissipated by axial conduction. The distribution of the temperature along the fuse-element is parabolic with the highest temperature ϑ_m being amidst. With increasing current increases simultaneously the value of ϑ_m . Upon reaching the critical current I_k, ϑ_m attains the fusing point of the used material, the fused metallic bridge pulls itself together under the influence of surface tension, and thus gives rise to the electric arc. Voltage conditions in the instant and place of the origin of the arc will change considerably. Before melting, the voltage gradient E in the fuse-element was

$$E = \varrho\,(1 + \alpha \cdot \Delta\vartheta) \cdot \sigma \qquad (1)$$

with α representing temperature coefficient of resistance, $\Delta\vartheta$ temperature rise of fuse-element in the moment of melting, σ current density. For Ag with σ = 100A/mm2 , we have E = 7,8 mV/mm. After the appearance of the arc, there exists

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at the ends of melted element an arc voltage U_o

$$U_o = U_k + U_a + E_o \cdot l \qquad (2)$$

As the arc, immediately after its origin, is very short (some tenths of mm), the third member in equation (2) can be neglected, and the arc voltage U_o will be determined by the sum of cathode U_k and anode U_a drop, which is of the order 50-200V per gap [1] Thus, the overvoltage does not occur if the heating-up of the fuse-element is slow (compare Tab.1).

The second extreme case is the adiabatic heating-up with high overcurrents, where the heat conduction does not make itself felt at all, and all the heat generated in the fuse-element is spent on its heating-up. The axial distribution of the heat has, in this case, a rectangular form. This case occurs if the conductor is heated-up with the current $I \geqslant 10 \cdot I_k$, where, in the sense of our previous consideration the critical current I_k is the lowest current which can melt the given conductor. The melting temperature is get along the whole length of the fuse-element all at once. The melted metal column behaves as any other column of liquid: its shape does not remain cylindrical, it changes to unduloidic one with contracted and expanded places, due to the influence of surface tension. Fuse-elements in transitory unduloidic phase have been studied especially by Polish authors, particularly by Nasilowski[2], [4] . The contracted places are heated-up more, the unstability of the unduloidic form is growing till the undulois finally disintegrates into n-drops, between which and the ends of the fuse-element, n+1 short arcs will be burning. The arc voltage will be

$$U_o = (n+1) \cdot (U_k + U_a) + E_o \cdot \sum_1^{n+1} l_i \qquad (3)$$

Compared with the previous case, the arc voltage will be (n+1)times higher and will surpass the source voltage. Between the slow and adiabatic heating-up of the fuse-element, there can exist transitory stages, in which the heat dissipation makes itself only partly felt in areas adjoining the margines of the fuse-element. Theoretically, there can occur cases ranging from the origin of two arcs up to a uniform desintegration along the whole length of fuse-element. Ossowicki [3] distinguished transitory stages in more details, taking as a basis the morphology of disintegration (Tab.1). Empiric formulas for determination of mean distance h, of two particles of a disintegrated fuse-element are given in Tab.2. Analyzing Tab.1, we come to the conclusion that the overvoltage occurs only when the fuse-element disintegrates on the whole length, with overcurrents of about (8 - 15)$\cdot I_n$. With further increase of the overcurrent increases also the overvoltage, because the dependence of the voltage on one elementary arc (i.e. sum of cathode and anode voltage drop) is growing linearly with the increasing current, as Dolegowski has proved experimentally [7].

The highest overvoltage can be awaited in the case of an instantaneous evaporation of the whole length of the fuse-element, with current-free interval. The current-free interval is caused by the fact that in a certain range of temperatures, e.g. for Cu between 2310 - 3500°C-, the vapours produced by the evaporation of the fuse-element are nonconducting. Thus, there occurs an ideal interruption of the circuit, and at the terminals of the melted fuse-element, appears the whole overvoltage given by the relation

$$U_p = L \cdot \frac{di}{dt} \qquad (4)$$

The rate of current rise di/dt is very high because it matters high overcurrents, and because the evaporation realizes in times non supassing 1 μs. The overvoltage can be as high as it breaks the discharge gap down. Another stage, i.e. evaporation of the wire with excess energy, so that the produced vapours are heated-up over the critical temperature becoming thus conducting, is characterized by the phenomenon that the current is not interrupted. Consequently, no current-free interval occurs. There occurs only one arc with one cathode and anode voltage drop. The value of the arc voltage will be determined, above all, by the voltage of the column, characterized by the high gradient (up to 100V/cm). Thus, the overvoltage lower than in the previous case can be awaited.

The preceding two cases of the interruption of the fuse - element, by means of its instantaneous evaporation, are only of theoretical importance. In fuses operating in existing networks current densities of the order 10^5 A/mm2 in the intervals shorter than 1 μs cannot be, in practice, attained.

Let us mention yet the last possibility, i.e. the adiabatic heating-up of the fuse-element preheated by the nominal current. In the starting stage, the distribution of the temperature was parabolic with the adiabatic heating-up being superimposed, so that the resulting distribution will have the form of a translated parabola. The melting of the fuse-element will not take place over the whole length, but only in its middle parts.If we compare the case of the short-circuit melting of the fuse-element from the cold and the warm stage (in both cases by means of the same short-circuit current), we find out, that the overvoltage will be lower with the fuse starting its function from the warm stage.

<u>FUSE-ELEMENT WITH CONTRACTED PARTS</u> In the case of the fuse-element with unvariable cross-section the number of interruption places and the height of the overvoltage depends on the value of the overcurrent as we saw in the previous paragraph. The overvoltages can attain considerable heights. For that reason, the up-to-date HRC LV fuses have fuse-element with contracted parts that predetermine places and number of arcs during melting. Theoretical consideration from the preceding paragraph, concerning the relation between the distribution of the temperature along the fuse-element and the number of interruption places, are partly valid even here : with parabolic distribution of the temperature, only the middle bridge melts and only one arc originates. With adiabatic heating-up, all the bridges remelt. To a demonstrable measure, this phenomenon can make itself felt only with fuses having a great number of bridges in a series.

Despite this, in fuses having a small number of bridges only, we also observe the influence of the preheating upon the overvoltage in breaking short circuits. In the case of PR type fuses with three bridges, it was experimentally found out that the mean value of the overvoltage coefficient decreased after preheating by nominal current by 8%, contrary to the case of operation from the cold stage. In this case, the decrease of the overvoltage cannot be explained by the decrease of interruption places. The fuse-element having been preheated, the fusing current decreased. The lowering of the current density in the moment of melting results, however, in lowering the arc-voltage per gap [7].

Let us refer to the question, how the design of the fuse-element influences the overvoltage. According to the theory, the number of bridges predetermines not only the number of arcs occuring after melting, but also the maximal overvoltage that can appear on the fuse. With increasing number of interruption places the overvoltage amplitude should according to the theory increase, too.

In our previous considerations, the fuse or its fuse-elements were taken into account separately without any respect to the influence of the external circuit. In fact, there is only a limited energy at disposal in the external circuit(mostly accumulated in the inductance), any the proportionality between the overvoltage amplitude and number of interruption places (length of the fuse-element, respectivelly)is valid only to a certain degree in dependence on the inductance of the circuit. Baxter [8] (Fig.1) has described this phenomenon and Hibner's [1] (Fig.2) recounted results confirmed it, too. With increasing number of interruption places increases also the energy, necessary fo their melting and for building up cathode spots, the process of melting itself is slowing down, and the part of energy which can manifest itself as the overvoltage is decreasing. Let us add to these problems one experience drawn from contact apparatuses. The division of the arc into a greater number of series small arcs contributes, after its entering a deionization grate, to limited overvoltage. The unstably burning arc shows numerous fluctuations of current and voltage caused, above all, by the great mobility of the arc column. Simplifying it we can say that the real length of the arc is being changed continuously. The gradient of the arc, as well, can change within large limits. On the other hand, the cathode and anode voltage drop is nearly constant in the large range of not only currents,but also of other conditions under which the arc burns. With the division of the arc into n-series arcs, the share of cathode and anode drops in the arc voltage increases, and in addition, with shortening the length of partial arcs, the possibility of the fluctuation of their length becomes smaller, which consequently results in considerable decrease of the arc voltage fluctuations.

THE INFLUENCE OF THE DESIGN OF THE FUSE ON THE OVERVOLTAGE

The influence of the filler has been studied only with the most common used filler - quartz sand - and namely, from the point of view of the granulation. Originally, Baxter published this relation [8]for copper wire, recently Hibner has done it for bands of different breadth. In all cases, the curve shows a maximum, the position of which dependends on dimensions of the fuse-element and on the granulation of the filler. The producer makes his choice of the granulation of the filler even from other standpoints (required breaking capacity, technology of filling the fuses, and economy) and possible high overvoltages reduces in another way, e.g. by the number of bridges. Technical literature dealing with the influence of other fillers than quartz sand is not known.

The use of copper instead of silver for the fuse-element does not influence substantially the limit overvoltage if the geometry of the fuse-element is retained. If we neglect the statistical fluctuations of the overvoltage coefficient in the range $\pm$ 0,1 the fuses with copper fuse-element shows the tendency to lower overvoltages.

The evaluation of the overvoltage must be carried out on the statistical basis, because the fuses show considerable dispersion of properties similar like all elements containing electrical arc. Statistical investigation of the overvoltages in the form of relative frequency diagrams in dependence on the overvoltage coefficient proved to be very useful.

The overvoltage coefficient is the relation of the overvoltage amplitude to the amplitude of the highest service voltage of the network, which lies usually by 1,1 U_n. On Fig.3a there is such a diagram for a member of the series of HRC fuses of the type PH (Czechoslovak production) with nominal current 50A, characteristic gTF, and on Fig 3b, the summary diagram for the whole series of fuses of the type PH. In both cases, the diagrams have the same shape corresponding to the normal distribution, and we can define two important coefficients of the overvoltage k:

- the most frequent coefficient of the overvoltage k^m, to which corresponds the greatest relative frequency,
- the limit coefficient of the overvoltage k^h that is the highest coefficient occurring in the set.

Analogous diagrams for other sizes of the series and types of fuses have a similar form, the approach to the normal distribution being the better the larger is the investigated set and the smaller is the difference of test parameters in individual experiments. In series of fuses, designed in the sense of IEC 269 as homogenous (proportionality of the cross-section of the fuse-element to its nominal current) not only the diagrams have the same shape, but also the most frequent and limit overvoltage coefficient have a constant value for all members of the series of fuses within the frame of statistical fluctuations($\pm$ 0,1) (see Fig.4 for the fuses, type PH, k^h). This is not the case in fuses where the homogenity of the series is not retained, as may be seen on Fig.5 (Roumanian fuses of the firm CILT).

INFLUENCE OF SERVICE PARAMETERS UPON THE OVERVOLTAGE

SERVICE VOLTAGE : In the preceding, we have shown that with a given design of the fuse-element, the overvoltage is influenced by the distribution of the temperature along the fuse-element, by the current and the inductance of the external circuit. The value of the overvoltage should be, consequently, constant with only the service voltage of the fuse being changed and other conditions unchanged. Experimentally found dependences of the overvoltage on service voltage are given by the producer and have a little increasing character. This phenomenon can be caused by different consumption of the energy necessary for loading parasite capacitances at the change of service voltage.

In the fuse with a shaped conductor the prospective current should have a very small influence on the overvoltage amplitude, because the influence of the current should show itself expecially in the value of cathode and anode voltage (see Equ. (3), the member of series arcs being predetermined. Experimentally found relations show within the frame of measurement accuracy and statistical dispersion independency of the overvoltage of the breaked current (Fig. 6,7). Influence of cos φ is small. It is caused by the decrease of the inductance and, consequently, by the amount of energy in the circuit (Fig. 8).

<u>MEASURED VALUES OF OVERVOLTAGES</u> (on the basis of measurements carried out by ourselves and those mentioned in technical literature) are given in Tab. 3. Fuses intended for the protection of semi-conductors show, of course, the lowest overvoltages while screw-plug cartridge fuses used for domestic installations the highest ones. The values attained in different countries do not differ substantially. We have found by means of the cathode oscillograph that the rate of rise of overvoltages lies by 650-9000V/ms, i.e.deep under the permissible rate of rise of normally used thyristors, which makes 200V/μs. Consequently, there is no reason for being afraid that electronic devices could be released un - intentionally due to the operation of fuses.

<u>Conclusion</u> Measured values of the overvoltages with existing fuses allow us to draw the conclusion that the technique of fuses coped successfully also with the protection of semi-conductor devices. As far as the theory is concerned, the problems of the influence of the number of interruption places upon the overvoltage are to be solved for making possible to elaborate an exact computation program for fuses even from this point of view.

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Tab. 1

Kind of desintegration	Overcurrent	Current deusity A/mm^2	Sample oscillogram [3] Over-current	Over-voltage	k	Ref.
single - arc	<(5 to 8) I_n	335	2,05 In	300V	1	[3]
chaotic	(4 to 12) In	1340	8,3 In	300V	1	[3]
drop	(5 to 15) In	1670	10,3 In	343V	1,15	[3]
mixed	(12 to 17) In	2820	17,4 In	530 V	1,75	[3]
striated	> 17 In	62 500	385 In	1100 V	3,76	[3]
evaporation of the whole lenght with current - free interval	~ 60 In	10^4				[5]
	~ 1000 In	$1,8.10^5$				[6]

Tab. 2

Kind of desintegration	Empiric formula for h [mm]	Range of validity	Ref.
drop	$h = \frac{16}{3} d$	Ag, Cu wires in air, d < 1mm	[4]
strip	h = 0,555 + 2,08d	Ag, Cu wires in sand	[4]
segment	h = 5,35	Cu wire, d = 1mm	[4]
of the band	h = 1,93 + 0,15b	Cu band, b = breadth	[1]

Tab. 3

Sort of fuses	Fuse origin	Maximal k^h	Maximal overvoltage V_m	Remark
HRC	Czechoslovakia	2,3	1650	
	Europe	2,4	1850	
	USA	1,95	1700	experiments
	USA	5,5	2000	catalogue
Semiconductor	Czechoslovakia	1,7	1200	
Screw - plug cartridge (type D)	Czechoslovakia	2,4	1900	
	Poland	4,3	2500	70 to 100 kA
	Holland	4,4	1400	

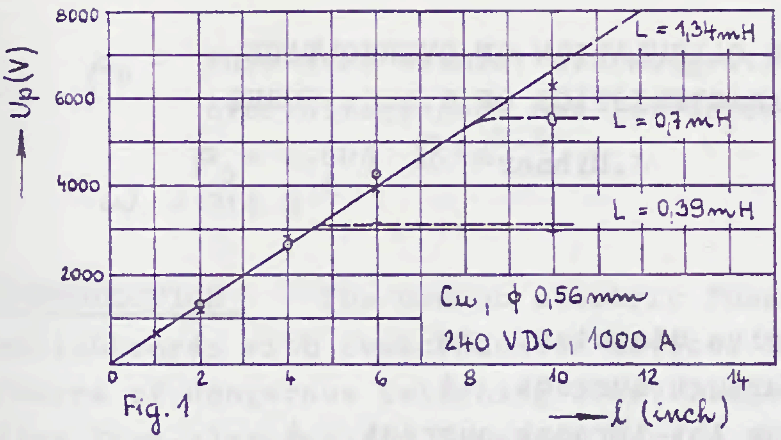

Fig. 1

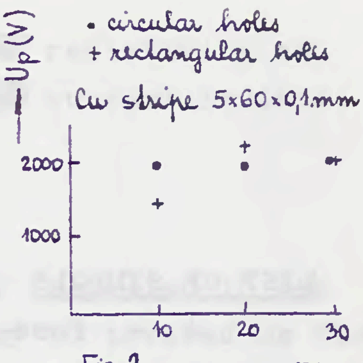

Fig. 2

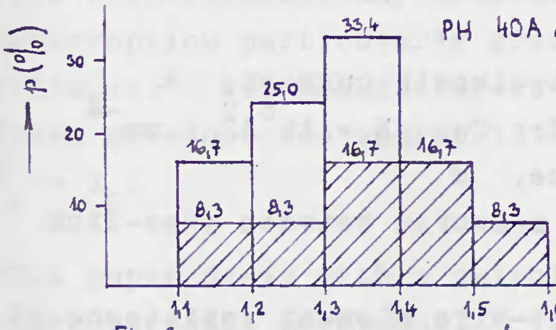

Fig. 3a

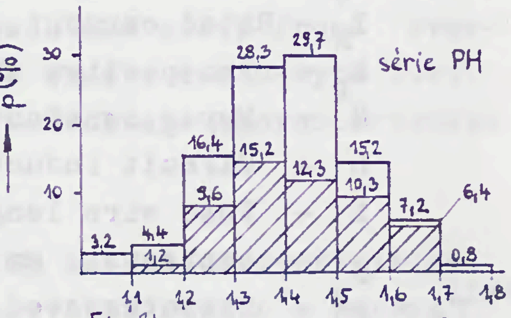

Fig. 3b

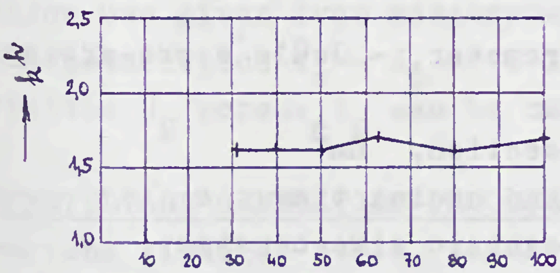

Fig. 4

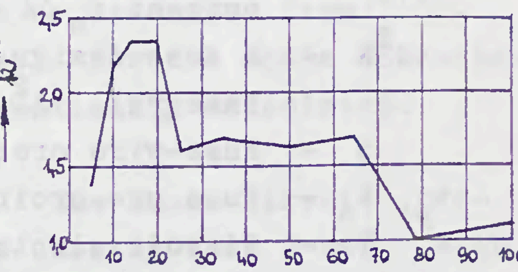

Fig. 5

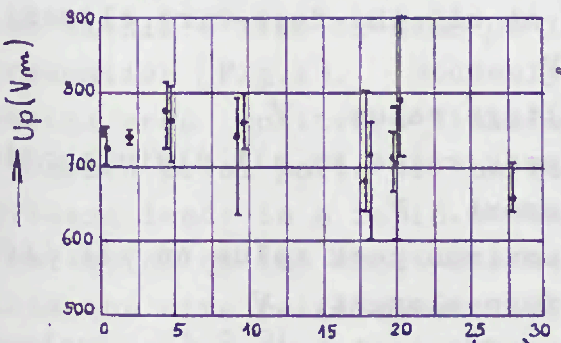

Fig. 6

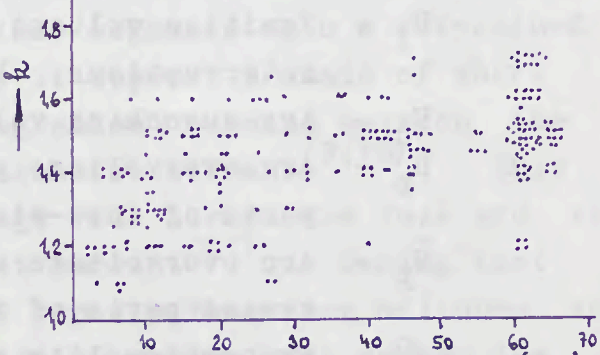

Fig. 7

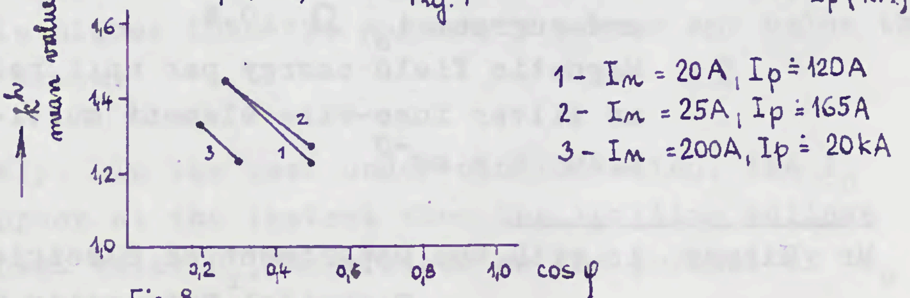

Fig. 8