THE CALCULATION OF OVERVOLTAGE CHARACTERISTICS OF H.R.C. FUSES

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LIST OF SYMBOLS

d - Fuse-wire diameter, mm

i_o - Let-through current, A

$\hat{i}_o$ - Maximum let-through current, A

I_N - Rated current, A

I_p - Prospective short-circuit current, A

K - Mayer constant, for Cu, $K = 10^5 A^2 \cdot s \cdot mm^{-4}$

L - Circuit inductance, H

l - Fuse wire length measured between fuse-link contacts, mm

$r_o = \frac{U_p}{i_o}$ - Disintegrated fuse-wire element resistance at the instant of arc overvoltage peak value U_p and current i_o, Ω

S^2K - A fuse design parameter, - Joule´s pre-arcing integral, $A^2 \cdot s$

S - Fuse-wire cross-section, mm^2

t_p, t_a - Fuse pre-arcing and arcing time, s

T - Circuit electromagnetic time constant, s

U - Source voltage, V

U_i - Ignition voltage at all the fuse-wire element interruptions, V

U_q - Arc-quenching voltage value, V

U_p - Arc overvoltage peak value on all disintegrated parts of fuse-element, V

$\hat{U}_p$ - Arc overvoltage maximum peak value on all disintegrated parts of fuse-element, V

β - Proportionality coefficient between overvoltage U_p and current i_o, $\Omega \cdot A^{0.5}$

ε - Magnetic field energy per unit required for copper or silver fuse-wire element multi-arc disintegration $W \cdot s \cdot mm^{-3}$

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ρ_0 - Fuse-wire element disintegration resistivity at overvoltage peak and let-through current instant,

$\rho_0 = 0.505\ \Omega \cdot A^{0.5}$

$\omega = 314\ s^{-1}$

INTRODUCTION The common electric fuses installed in the switchboards with semiconductor devices may be treated as the source of dangerous switching overvoltages. Fuse-links with wire fuse-elements may generate during short-circuit current interruption particularly great peak and steep front overvoltages. But manufacturers data sheets for D-type l.v. fuses give not the appropriate overvoltage characteristics $\hat{U}_p - I_p$.

This paper deals with a calculating method of overvoltage characteristic prediction. The previous author's papers(1÷6) enabled the U_p values calculation for a current i_o only which value was given from measurements or estimated from(7,8) characteristics $\hat{i}_o - I_p$ of a fuse. Now the whole characteristics $\hat{U}_p$ versus I_p can be mathematically calculated.

OVERVOLTAGE GENERATION PROCESS The short-circuit pre-arcing times of h.r.c. fuses are shorter than 5 ms. With large enough short-circuit current the fuse-wire disintegrates within a time of some μs into segments with a determined graduation (Fig.1). Suddenly it appears a chain of short serial arcs multi-arc disintegration burning between the remained metal parts of the fuse-wire element(9,10). This process leads to a rapid voltage rise across the fuse and to limitation of the short-circuit current(11). During that time the wire resistance rises rapidly from some miliohms to some ohms(1,2,3). Normally if the arc voltage during the arcing time is higher than the momentary source emf value the current will break.

Approximatively, in the case under consideration, the i_o value will appear at the instant when the ignition voltage reaches its peak value U_i, understood as the product of i_o

multiplied by r_o. On the other hand, at the instant of final arc-quenching the quenching over-voltage U_q may appear. In the case of fuses with multi-arc disintegration its value normally is smaller than the ignition voltage U_i.

For d.c. and a.c. the element disintegration and overvoltage generation mechanism is analogous (Fig.2).

BASIC RELATIONS FOR THE OVERVOLTAGE CALCULATION According to the principle of the resistance method[1,2,3] Fig.2, the overvoltage can be calculated using the following relation:

$$U_p = \rho_o l \sqrt{\frac{i_o}{S}} = \frac{\rho_o l}{\sqrt{S}} \sqrt{i_o} = \beta \sqrt{i_o} \qquad (1)$$

which is valid for

$$\varepsilon = \frac{L i_o^2}{2 l S} \geqslant 25 \ \frac{Ws}{mm^3}, \quad i_o \geqslant 50 I_N \qquad (2)$$

The relation (1) and conditions (2) are given in papers[2,3,6]

In order to get from relation (1) the characteristic $U_p - I_p$ it is necessery to involve a current i_o in parameter $S^2 K$ and the circuit current I_p.

The parameter β one may determine for a given fuse-link from the values ρ_o, l and S. The parameter should normally be given in manufacturers data sheets to enable the estimation of characteristic $U_p - I_p$.

A.C. $\hat{U}_p - I_p$ CHARACTERISTIC For low-current ratings up to abt 20 A the fuse-wire dia. is not greater than 0.4 mm. Than the $S^2 K$ value is low enough and $i_o < 0.5 \ I_p$, so one can write the following simplification

$$i = \sqrt{2} I_p \sin \omega t \approx \sqrt{2} I_p \omega t \qquad (3)$$

For

$$\int_0^{t_1} i^2 dt = S^2 K \qquad (4)$$

from (3) it follows

$$\hat{i}_o = 11 \sqrt[3]{S^2 K I_p} \qquad (5)$$

The additional condition, which determines practically precise calculation results by using the relation (5) is

$$\frac{S^2 K}{\frac{2\pi}{\omega} I_p^2} < 0.01 \qquad (6)$$

From (1) and (5) we finally may get the relation $\hat{U}_p - I_p$

$$\hat{U}_p = 3.3 \beta \sqrt[6]{S^2 K I_p} \qquad (7)$$

Exceptly the condition 6 there must be yet fulfilled the conditions concerning the fuse wire disintegration energy [2] but written in a different manner as function of parameter S^2K

$$\mathcal{E} = 16 \frac{L}{l} \sqrt[6]{S^2 K I_p^4} \cdot 10^3 > 25 \frac{Ws}{mm^3} \qquad (8)$$

$$S^2 K I_p > 94 I_N^3 \qquad (9)$$

D.C. $\hat{U}_p - I_p$ CHARACTERISTIC For the same assumption as for a.c. the short-circuit d.c. current shape for $t/T < 0.1$ one can write

$$i = I_p\left(1 - e^{-\frac{t}{T}}\right) \approx I_p \frac{t}{T} \qquad (10)$$

From (4) and (10) it follows

$$\hat{i}_o = 1.44 \sqrt[3]{\frac{S^2 K \, I_p}{T}} \qquad (11)$$

The dependence is valid for

$$\frac{S^2 K}{I_p^{\,2} T} < 0.1 \qquad (12)$$

From (1) and (11) we may get the relation for $\hat{U}_p - I_p$ characteristic

$$\hat{U}_p = 1.2\,\beta \sqrt[6]{\frac{S^2 K \, I_p}{T}} \qquad (13)$$

The additional conditions which should be taken into account beside (12) are the following

$$\mathcal{E} = 297 \frac{L}{l} \sqrt[6]{S^2 K \left(\frac{I_p}{T}\right)^4} > 25 \frac{Ws}{mm^3} \qquad (14)$$

$$\frac{S^2 K I_p}{T} > (35\, I_N)^3 \qquad (15)$$

<u>EXEMPLARY $\hat{U}_p - I_p$ CHARACTERISTIC</u> Fig.3 shows the exemplary $\hat{U}_p - I_p$ a.c. and d.c. characteristics for some D-type

fuses Table 1 in range of 2 - 20 A calculated using the relations (7) and (13). The idendical characteristics can be drawn, if existing in dependence (1), i_o values will be calculated from characteristics $\hat{i}_o - I_p$ (7,8).

Table 1

Design parameters of D-type fuses Fig.1, for which the $\hat{U}_p = f(I_p)$ characteristics shown in Fig.3 have been calculated.

I_N	A	2	4	6	10	16	20
S^2K	$A^2 S$	4	24	65	300	894	2880
β	$\Omega A^{0.5}$	311	200	155	106	81	60

The carried out experimental test results with I_p = 1800 A and U = 260 V show a good agreement with calculations.

Generally it may be pointed out, that agreement between the calculated and measured $\hat{U}_p - I_p$ characteristics mainly depends from accuracy of i_o value determination, particularly for greater I_p values.

If the i_o values is accurate enough than the U_p value is accurate enough too. This conclusion goes from the author's examination of the dependence (1) in the following very wide parameter range:

- let-through currents from 0.1 kA to 20 kA
- current densities from 2 $kA \cdot mm^{-2}$ do 50 $kA \cdot mm^{-2}$
- source voltages from 0.5 U to 2 U
- energy per unit from 25 $W \cdot s \cdot mm^{-3}$ to 500 $W \cdot s \cdot mm^{-3}$
- circuit power factor $\cos \varphi$ or circuit inductance L in compliance with condition (2).

CONCLUSIONS The method suggested by the author makes possible the calculation of probable values of overvoltages generated by fuses with fuse-wire elements for any rated current in any electric circuit using formulae (1), if i_o value is known from measurements or from $\hat{i}_o - I_p$ characteristic

The maximum error statistically determined at a confidence level of 0.95 while using the formulae (1) for calculation of peak voltage does not exceed 16 %[2,3] when the conditions regarding the disintegration energy and the element disintegration density are complied with (2).

This same calculating method of $\hat{U}_p - I_p$ characteristic may be used, if there are known relations i_o versus S^2K, I_p and T. In some cases, for which dependences[6,8,9] and[12,14,15] are fulfiled, one can obtaine the good results in the estimating of $\hat{U}_p - I_p$ from relations (7) and (13).

In order to enable the users to carry out overvoltage calculations on the basis of the formulae (1,7,13) the fuse manufacturers should make known some essential parameters of fuse elements such as the S^2K and β if more detailed parameters such as e.g. S, K and the quenching materials nature can not be given. In the lack of suitable catalogue data the fuse element parameters can be with sufficient accuracy determined by direct measurement of a dismantled fuse.

Practical application of the presented method of calculating overvoltages could diminishe labour consuming and expensive laboratory tests and accelerate working out catalogue data for fuses of any new design.

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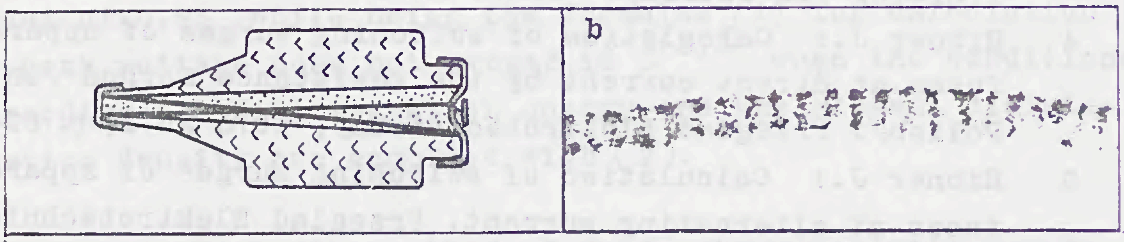


Fig.1. D-type fuse link with a wire element without notches (a) and element fragments after breaking a short-circuit (b)
b - vitrification with striated disintegration at the total element length when conditions (2) are complied with.

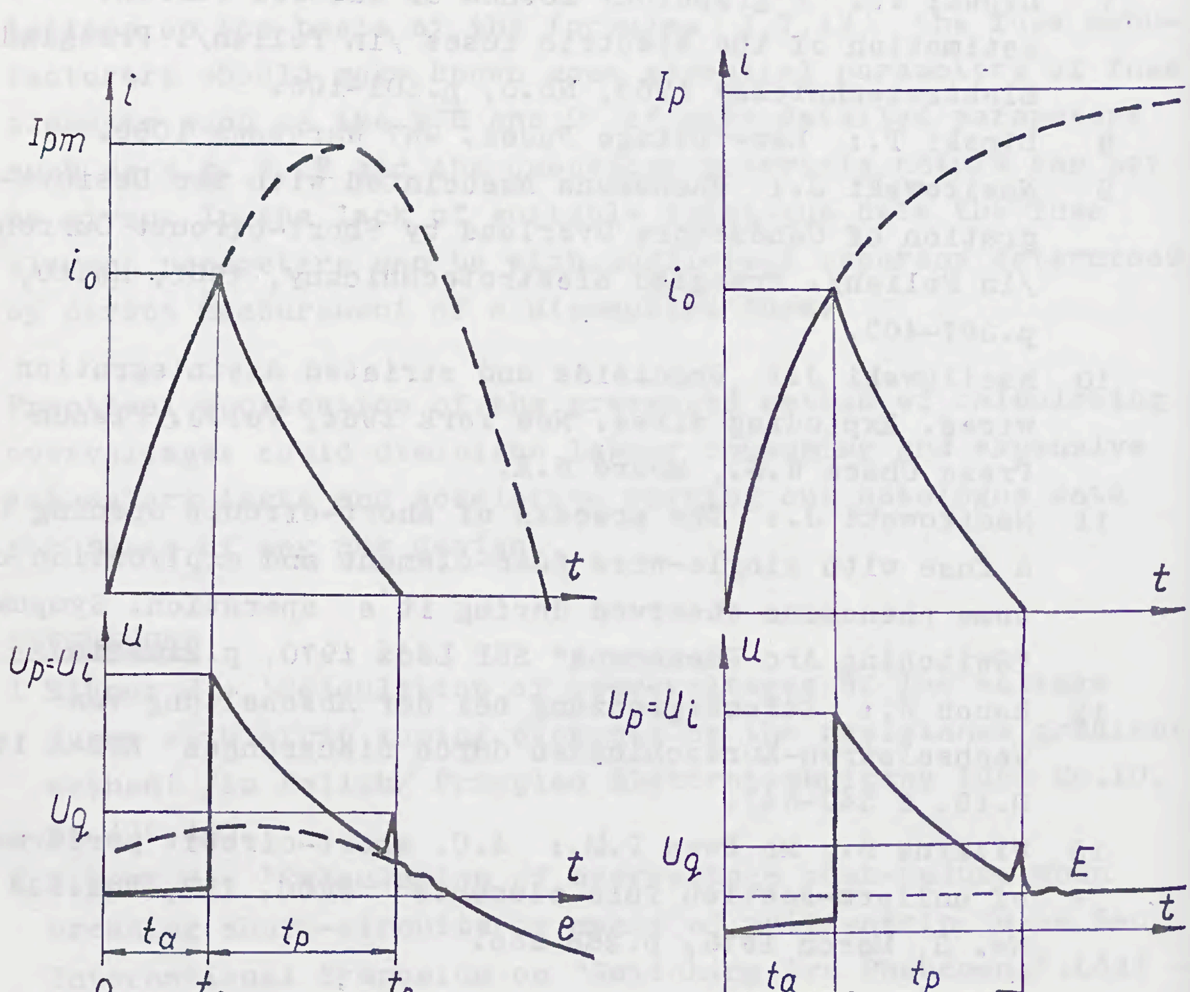
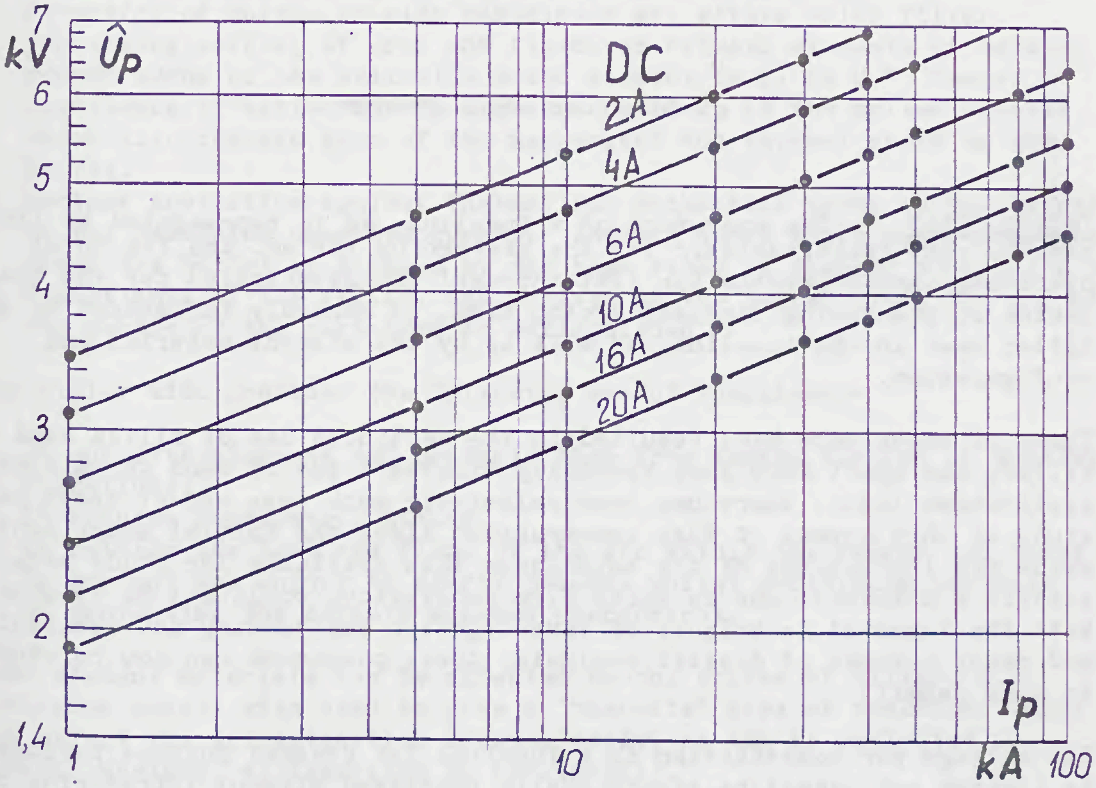


Fig.2. Simplified current and voltage course at D-type fuse operation in AC and DC circuits.



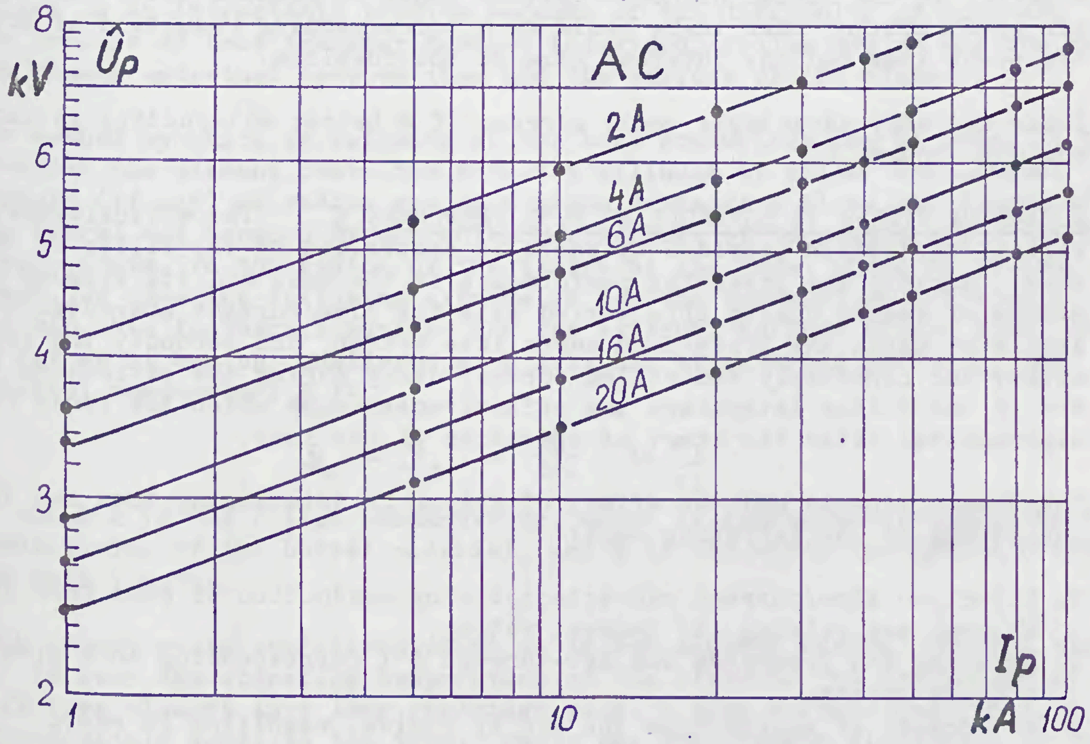


Fig.3. Fuse peak arc voltage $\hat{U}_p - I_p$ characteristic.
DC circuit, U_N = 500 V, T = 5 ms, $I_p \leqslant$ 100 kA.
AC circuit, U_N = 500 V, 50 Hz, $\cos\varphi$ = 0.1,
$I_p \leqslant$ 100 kA RMS.