CALCULATION OF THE COURSE OF THE CURRENT AND VOLTAGE OF A CURRENT-LIMITING FUSE

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INTRODUCTION The problem connected with the calculation of the voltage transient across an electric fuse and of the current in a circuit with a short-circuit cut-out by the electric fuse is dealt with by several authors [1,3,4,9,10,11,12, 16]. The first to develop a calculation method of breaking current transients by low voltage tape type fuse cut-outs for overload and small short-circuit currents was Kroemer [11] and for short-circuit currents were Gruner Nielsen and Holm Lersen [9]. They attempted to relate the voltage transient across a cut-out in a low voltage circuit with the design parametres of the cut-out. The methods developed by these authors have, however, a limited range of application as they can only be used for a gross evaluation of overload current and small short-circuit current breaking for a given type of fuses. [9,11]

Difficulties bound with relating design parametres of a cut-out with transients of the current flowing in the circuit of the voltage across the cut-out and of the power and energy evolved in the cut-out, induced some authors to seak for calculation methods allowing for a more complete determination of electric transients occurring under short-circuit conditions in circuits provided with cut-outs which would be based on the assumption of a simplified voltage waveshape across the cut-out [3,4,12]. They assume, namely, that the voltage waveshape across the cut-out has the form of a given geometrical figure, e.g. of a rectangle or triangle. In result these authors obtained certain interesting conclusions on arc extinction, on the limitation of the short-circuit current and the influence of the voltage waveshape on the breaking performance value and of the Joule integral value.

The above quoted authors do not state what design parametres of a cut-out influence the appearence of a given voltage waveshape occurring across it. Therefore, as results from the survey presented, the up-to-date calculation methods do not allow, in practice, for the calculation of current and voltage transients appearing on a current limiting cut-out having complex design parametres of the fuse, especially, for the case of short and heavy overloads.

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Under these circumstances, a calculation method is suggested which would take into account the effect of the dimensions of the fuse element on the waveshapes of the voltage across the cut-out and of the current flowing in the circuit. This calculation method is developed basing upon the investigation and an analysis of the short-circuit current breaking process by a fuse cut-out provided with band and wire fuses with necked cross-section and placed in a sand extinction medium.

The analysis of the breaking process is carried out using differential equations resulting from Kirchoff´s law for an a.c. circuit:

$$U_m \sin(\omega t + \psi) - u_p(t) = L \frac{di}{dt} + R\, i \qquad (1)$$

where U_m - voltage of source, peak value expressed in V, ω - pulsation expressed in 1/s, t - time in s, ψ - phase angle shift between passage of source voltage through zero and the moment of short-circuit occurance in electrical degrees, $u_p(t)$ - voltage across cut-out in V, L - /constant/ induction in H, R -/constant/ resistance of circuit in ohms, i - current flowing in circuit in A.

The range of the analysis is limited to the case of short-circuit clearance by fuse cut-outs with band and wire Cu and Ag fuses with ratio of necked cross-section to that not necked equalling or smaller than 0.6. The fuses have a number n of identical neckings.

A the end of every arcing period voltage drops occur at the electrodes which for both the anode and the cathode are represented by the voltage U_B. The number of arcs equals the number n of neckings. Under these assumptions, the relation describing the voltage waveshape across the cut-out can be expressed by the following equation:

$$u_p = n\left(U_N + l \cdot E\right) \qquad (2)$$

where u_p - voltage across cut-out in V, n - number of neckings of fuse number of arcs , U_B - voltage drop at electrodes in V, l - length of a single arc in cm, E - electric field strength, average voltage gradient in V/cm.

Substituting expression (2) in equation 1 we obtain:

$$U_m \sin(\omega t + \psi) - L \frac{di}{dt} - Ri = n\left(U_B + lE\right) \qquad (3)$$

In result of an analysis made and of laboratory tests the quantities U_B, l and E could be determined as a function of certain physical parametres characteristic for the arc in the cut-out and as well as for the geometrical dimensions and the material of the fuse including copper and silver fuses.

LABORATORY TESTS A series of indentical cut-out models, provided with Cu and Ag fuses having shapes and dimensions according to fig.1, were prepared. The fuses were immersed in quartz sand of 0.2 to 0.4 mm grain size. The fuses were tested in the test circuit specified in fig.2.

The power of the source and the constants R and L of the test circuit fig.2 allowed for the obtention of the following test parametres foreseen by the programme: prospected current I_p=0.3 to 60 kA, cosφ = 0.1 to 0.35, recovery voltage U_p=100 to 240 V or 600 to 1800 V.

The tests of cut-outs by the method of arcing stoppage were carried out switching on by the short-circuiting switch Z_1 the circuit with cut-outs B_1 and B_2 and, thus, initiating in the cut-out B_1 the arcing process. Next, at a given moment after the appearance of the arc the arcing process was stopped by closing the switch Z_2. During the test series of identical cut-outs the latter switch was closed at different delay times in reference to the moment of arc firing. These times were chosen so as to assure a uniform distribution of times to closing of the switch. The tests carried out by this method are illustrated by oscillogrammes of fig. 3.

ANALYSIS OF TEST RESULTS

Determination of voltage U_B The voltage drop U_B at the electrodes of an arc appearing within a cut-out was determined by extrapolation of the function U=f(l) see fig. 4 to its intersection with the axis of ordinates.

It may be seen in this figure that at small arc length the voltage increments are approximately proportional to arc length increments. Thus, we can write:

$$u_p = U_B + l \frac{du}{dl} \qquad (4)$$

where u_p - voltage across cut-out in V, U_B - voltage drop at electrodes in V, l - arc length in cm, du/dl = E - electric field strength in arc column in V/cm.

The quantities U_B and E in expression (4) are functions of tests parametres /of the current/ and of design parametres of the fuse [5,6,7,8]. When investigating relation (4) it was stated that:

a/ for the range of current densities throughout the fuse cross-section S not exceeding 8 kA/mm^2, U_B is a function of the current, U_B = f(i)- see fig. 6,

b/ for the range of current densities thronghout the fuse cross-section S of 8 to 20 kA/mm^2, U_B is a function of the current density throughout the fuse cross-section, U_B = f (i/s) - see fig. 7.

The function $U_B = f(i)$ represented in fig. 6 is an exponential relation.

Establishing in the diagramme the origin of the system of coordinates at the point of 20 A the relation $U_B = f(i)$ may be represented by an analytic equation by the expression:

$$U_B = \Delta U_1 + k\, i^{\vartheta} \tag{5}$$

where U_B - voltage drop at electrodes in V, ΔU_1 - constant component of the voltage drop at electrodes equalling 20 ± 5V, k - coefficient equalling 1,5, ϑ - exponent equalling 0.39.

Fig.6 represents the relation $U_B = f(i/S)$. It may be seen that for the range of current densities of 8 to 20 kA/mm^2 the relation can be represented as a straight line of a slope $\rho_B = 4.18 \pm 0.25 \cdot 10^{-5} \Omega \cdot cm^2$. The extrapolation of this straight line to its intersection with the axis of ordinates determines the point $\Delta U_2 = 30 \pm 5$ V.

The analytic form of the equation of the regression line for the relation $U_B = f(i/S)$ for the current density of 8 to 20 kA/mm^2 may be represented by the following expression:

$$U_B = \Delta U_2 + \frac{i\, \rho_B}{S} \tag{6}$$

where ΔU_2 - component of voltage drop at electrodes independent of current and equalling 30 ± 5V, ρ_B - slope of straight line in Ω cm^2, S - fuse cross-section equalling the arc cross-section S_B in the electrode zone in mm^2. 8

It results from expression (6) that for the current density range of 8 to 20 kA/mm^2 the slope of the straight line, is constant and has the dimension of resistivity of the electrode zone expressed in Ω cm^2 (and not in Ω cm as the deepness of the electrode zone was not established).

As can be seen, U_B can be calculated from the expressions (5) or (6). In doubtful cases, the relation $S_B = f(i)$ is decisive under the following form

$$S_B = c_1 \cdot i^{\varepsilon} \tag{7}$$

in which the coefficients c_1 and ε amount to:

$c_1 = 1.05 \pm 0.1\ 10^{-3}$, $\varepsilon = 0.730 \pm 0.03$.

Thus, when the cross-section S_B calculated from expression (7) equals or exceeds the cross-section S, $S_B \geqslant S$, expression (6) obliges, and when the cross-section S_B is smaller than the cross-section S, $S_B < S$, the expression (5) is valid.

Determination of arc length l The velocity of elongation of the arc depends on the material of the fuse, its temperature, the cross-section and the power of the arc. The energy necessary for fusing a section of length dl /neglecting the emission of heat to the ambiance as it is a short-circuit that we are considering / results from the heat balance equation:

$$dl \cdot S \left[C_v \cdot \triangle T + h + h' \right] = c_2 i^2 \; R_B \cdot dt \tag{9}$$

where dl - elementary length of fuse in cm, S - crosssection of fuse in cm^2, C_v - specific heat of metal in solid state per unit volume $\frac{Ws}{{}^{\circ}C\ cm^3}$, h - latent heat of fusion of metal per unit volume $\frac{Ws}{cm^3}$, h' - empirically determined quantity taking into account the energy of vaporisation of the metal and that of transformation of the thermal energy into the kinetic energy of metal vapour $\frac{Ws}{cm^3}$ [7,8] $\triangle T = T_1 - T_2$, T_1 - - metal fusion temperature, T_2 - temperature of fuse heated by Joule's heat, C_2 - proportionality factor, i - current A, R - resistance of electrode zone of arc in ohms, dt - time in s.

After transformation expression (9) takes the following form:

$$\frac{dl}{dt} \left[C_v \cdot \triangle T + h + h' \right] = \frac{C_2 \; i^2 \; R_B}{S} \tag{10}$$

Expression (10) represents the relation between the thermal power evolved within the fuse and the power density at the electrodes. The following data are necessary for solving this relation:

$\frac{dl}{dt}$ - velocity of arc elongation in cm/s corresponding to the instantaneous value of the current i, see fig. 5,

T_2 - temperature of fuse heated by Joule's heat corresponding to the instantaneous current value i,

R_B - resistance of electrode zone of arc as function of current.

These data have been determined from the short-circuit tests considered in Chapter 2.

The elongation velocity of the arc or of the arc gap dl/dt corresponding to the instantaneous value of the limited current i and at the moment t_1 is determined from the diagramme of fig. 5 as the slope of the tangent to the curve $l=f(t)$ at the point having coordinates t_1 and l_1.

The temperature T_2 of the fuse heated by Joule's heat corresponding to the instantaneous value of the current and at the moment t_1 can be determined from the expression:

$$T_2 = \frac{\exp \frac{\alpha \rho_o}{S^2 C_v} \int_{t_o}^{t_1} i^2 dt - 1}{\alpha} \tag{11}$$

where T_2 - temperature of fuse in ^oC, ρ - resistivity of the fuse metal in ohm·cm, α - temperature factor of resistance in solid state $1/^oC$, C_v - specific heat of the metal of the fuse in $\frac{W_s}{^oC\ cm^2}$.

Expression (11) results from Mayer's formula [15].

For an arc resistance R_B in the electrode zone the following expression may be suggested:

$$R_B = \frac{U_B}{i} \tag{12}$$

By substituting in equation (10) the expression (12) we obtain the following relation:

$$\frac{dl}{dt}\left[C_v \cdot \Delta T + h + h'\right] = \frac{C_2\, i\, U_B}{S} \tag{13}$$

in which the factor C_2 determined by the method of minimum squares amounts to:

$$C_2 = 0.18 \pm 0.01$$

By transforming expression (13) we obtain the relation between the arc elongation velocity on current, temperature and the fuse material constants having the following form:

$$\frac{dl}{dt} = \frac{C_2\, i\, U_B}{S\left[C_v \cdot \Delta T + h + h'\right]} \tag{14}$$

After separating the variables and integration we obtain:

$$l = C_3 + \int_{t_z}^{t_1} \frac{C_2\, i\, U_B\, dt}{S\left[C_v \cdot \Delta T + h + h'\right]} \tag{15}$$

where l - length of fusion of fuse element in cm, t_z - firing moment, t_1 - moment at which the arc attains the length l_1, C_3 - constant having the dimension of the arc length in cm. It determines the necking length p.

Determination of voltage gradient E It results from the author's works that at the beginning of the breaking process the voltage rate of rise du/dt depends on the arc power p and on the value of Joule's energy evolved in the fuse at the moment of occurrence of the short-circuit, i.e. that a correlation exists between the voltage rate of rise and the arc power [6,8]

$$\frac{du}{dt} = f(P)_{T_1 = \text{constant}} \tag{16}$$

Taking expression (16) into account and differentiating expression (2) we obtain for the initial section of the process for growing current values

$$\frac{du}{dt} = \frac{d \cdot U_B}{dt} + \frac{dl}{dt}E + \frac{dE}{dt}l = f(P) \tag{17}$$

The arc power can be expressed by:

$$P = \frac{i^2}{G_k} \tag{18}$$

where G_k - conductivity of arc gap.

Conductivity of the arc column is a function of the current [10,16]

$$G_k = f(i) \tag{19}$$

Introducing to the formula (18) expression (19) we obtain

$$P = i^2 f(i) \tag{20}$$

or

$$P = f_2(i^\beta) \tag{21}$$

Substituting in equation (21) the expression (17) and taking into account that the voltage drop at the electrodes U_B in a wide range of current variation, hence, also of time up to the moment considered, changes but slightly. In consequence, the index dU_B/dt appearing in expression (17) is very small and we can assume

$$\frac{dU_B}{dt} = 0$$

and after setting E before the parenthesis we obtain:

$$\frac{du}{dt} = E\left(\frac{dl}{dt} + \frac{dE}{dt}\frac{l}{E}\right) = f_2(i^\beta) \tag{22}$$

It may be seen from 22 that the voltage variation rate across the cut-out depends on two components:

- the component resulting from arc length increase at a constant voltage gradient,

- the component resulting from the voltage gradient increase at a constant arc length.

By transforming expression (22) to the form:

$$E = \frac{f_2(i^\beta)}{\frac{dl}{dt} + \frac{dE}{dt}\left(\frac{1}{E}\right)} \tag{23}$$

we obtain the relation between the electric field strength and the current as well as the quantities $\frac{dl}{dt}$ and $\frac{dE}{dt}$ characteristic for the extinction performance of the cut-out.

Introducing in the expression (23) $\frac{dE}{dt} = 0$ (E=const.) we obtain the relation between the electric field strength and the current as well as the fusion velocity of the fuse.

$$E = \frac{f_3(i^\beta)}{\frac{dl}{dt}} \tag{24}$$

Introducing in expression (23) $\frac{dl}{dt} = 0$ (l=const.) we obtain the current at a constant length of the arc (This case occurs after a complete fusion of the fuse element and before the arc extinction within the cut-out .

$$E = \frac{f_4(i^\beta)}{\frac{dE}{dt}\left(\frac{1}{E}\right)} \tag{25}$$

Respective numerical data for the relations E = f(i) according to the expressions (24) and (25) were established from tests. Numerical data for the relation E=f(i) according to the expression (25) were obtained from the analysis of oscillogrammes of current breaking at a constant length of the arc. This analysis allowed for plotting the diagramme E = f(t) represented in fig.8. This relation can be expressed as an exponential function:

$$E = E_o \exp t/\theta_1 \tag{26}$$

where E - electric field strength in V/cm, E_o - electric field strength at the moment t=0, θ_1 - time constant characteristic for the field decay in the arc column due to heat cumulation in extinction medium.

After differentiation of the expression (26)

$$-\frac{dE}{dt} = -\frac{E_o}{\theta_1} \exp {}^{-t}/\theta_1 \tag{27}$$

and substitution of (26) and (27) in expression (25) we obtain:

$$E = \frac{f_4(i^\beta)}{C_4 \frac{1}{\theta_1}} \tag{28}$$

where C_4 - constant.

Numerical data corresponding to the relation $E = f(i)$ according to expression (24) have been obtained from the diagramme $E \cdot \frac{dl}{dt} = f(i)$ represented in fig.9. The product $E\frac{dl}{dt}$ is represented in this diagramme as a function of the current referred to the double width of the fuse and taking its thickness as parametre. The analysis of measuring results represented by the diagramme allows for rewriting expression (24) in the following form [8]:

$$E = \frac{C_5\left(\frac{i}{2F\,\ln a/a_o}\right)^{\beta}}{dl/dt} \tag{29}$$

where C_5 - proportionality factor, a_o - critical thickness equalling 0.0032 cm, a - fuse thickness in cm, F - width of fuse in cm.

For symmetry purposes of expressions (28) and (29), the current in the relation $E = f(i)$ in expression (28) may also be referred to the dimensions of the fuse:

$$E = \frac{C_6\left(\frac{i}{2F\,\ln a/a_o}\right)^{\beta}}{C_4\,\frac{l}{\theta_1}} \tag{30}$$

Substituting expressions (29) and (30) in expression (23) we obtain:

$$E = \frac{C_7\left(\frac{i}{2F\,\ln a/a_o}\right)^{\beta}}{\frac{dl}{dt} + C_4\,\frac{l}{\theta_1}} \tag{31}$$

In the above considerations it was assumed that the conductivity of the arc column is a function of the current. Fig.8 displays that this conductivity is also a function of time and can be expressed by the equation:

$$G_k = G_o \exp{}^{-t}/\theta_1' \tag{32}$$

where G_k - conductivity of arc column in 1/ohm, G_o - conductivity of arc column at the moment t=0, θ_1' - time constant of the decay of the conductivity of the arc column. The diagramme shows that $\theta' = \theta$.

Thus, taking into account the relation (32) the expression (31) will have the form:

$$E = \frac{C_8\left(\frac{i}{2F\ \ln\ a/a_o}\right)^{\beta}}{\left(\frac{dl}{dt} + x\right)\exp{}^{-t/\Theta_1}} \qquad (33)$$

where C_8 - proportionality factor equalling $1{,}1\cdot10^{-2}$, β - exponent equalling 2 ± 0.2, F - width of fuse in cm, a - thickness in cm, $a_o=0.0032$ cm, Θ_1 - time constant equalling 1.6 to $6.2\cdot10^{-3}$ s, $X=C_4\frac{1}{\Theta_1}$; for simplification reasons it was assumed that x is a constant amounting to $x = 111\pm1$.

The mentioned numerical values apply to cut outs with band fuses of thickness 0.005 to 0.03 cm. For wire fuses, the value C_8 amounts to $1.7\cdot10^{-2}$, and 2F and ln a/a_o should be respectively substituted by terms $\pi\cdot d$ and $z\cdot\ln d/d_o$ where d- wire diameter in cm /in the range from 0.006 to 0.06 cm/, z - number of parallel wires, d_o - critical diameter equalling 0.0032 cm.

The expression (33) can be applied only in approximate calculations as it does not take account of the phenomenon of arc hysteresis. This phenomenon can be taken into account by introducing in the expression (33) of supplementary relations resulting from Mayr's report [14]. When these relations are introduced and after simplifications made the expression (33) will have the form [8] :

$$E = \frac{C_8\left(\frac{i}{2F\ \ln\ a/a_o}\right)^{\beta}\exp^{t/\Theta_2}}{\left(\frac{dl}{dt} + x\right)\exp^{-t/\Theta_1} + \frac{\int_{t_z}^{t_k} i^2 \exp^{t/\Theta_2}dt}{E_{max}\cdot i_{max}\cdot\Theta_2}} \qquad (34)$$

where Θ_2 - arc time constant according to Mayr, i_{max} - peak-value of limited current, E_{max} - electric field strength corresponding to i_{max}, t_z - arc firing moment, t_k - moment at which the breaking process is ended.

Taking into account the relations (5), (15) and (34) we obtain finally for (3) the expression:

$$U_m \sin(\omega t + \Psi) - L\frac{di}{dt} - Ri = n(\Delta U + k\,i) + n\left[C_p + \int_{t_z}^{t_k}\frac{C_2}{C_v\Delta T + h + h'}\right]\left(\frac{i\,U_B}{S}\right).$$

$$\cdot \frac{C_8 \left(i \frac{1}{2F} \cdot \frac{1}{\ln a/a_0} \right)^{\beta} \exp^{\,t/\Theta_2}}{\left(\frac{dl}{dt} + x \right) \exp^{-t/\Theta_1} + \frac{1}{E_{max}\, i_{max}\, \Theta_2} \int_{t_z}^{t_k} i^2 \exp^{\,t/\Theta_2}\, dt} \qquad (35)$$

An algebraical solution of this equation does not exist. It may only be solved by the iteration method on a digital computer, preparing of course a suitable calculation programme. The arc firing moment can be calculated by means of the method quoted in report [13].

CALCULATION EXAMPLES The fig.11 represents the voltage and current waves calculated by means of expression (35) - dotted line. The continous line displays the same curves from oscillographic records. The calculated and the oscillographically recorded curves concern the same design parametres of the cut-out and the same test conditions. The fuses type H_n, a = 0.02 cm, F = 1 cm, $S_z/S=0.5$, N=8. The error in the calculation of the fuse length does not exceed ±5%. The particular coordinates of the calculated current and voltage curves and the respective coordinates of actual curves do not differ by more than 10%.

Fig.10 shows four curves A,B,C,D of voltage and current calculated according to expression (35) for the same circuit parametres. The calculations concern fuses typ H_n of design parametres: a=0.02 cm, F=1 cm, $S_z/S=0.5$ differing only by the number of overloads n.

CONCLUSIONS

a/ The proposed method allows for the calculation of the following electric and design parametres of the cut-out:

1/ the breaking transients and the current flowing in the circuit, the voltage across the cut-out, the power and energy of the arc,

2/ the dimensions of the fuse element: its length, width and thicknes, as well as the number of neckings.

b/ The calculation method allows for the determination of the fuse length required in the given short-circuit conditions and for the correct breaking performance, under preset other design parametres, with an error range of ±10%.

c/ The calculation method allows for the choice of the most advantageous voltage waveshape, for a given type of cut-out, by a suitable shaping of the fuse element.

References

A. Books

1. Baxter H.W.: Electric fuses E. Arnold London 1950

2. Lipski T.: Low voltage cut-outs, PWNT Warszawa 1968

B. Reports, periodicals and other

3. Boehne E.W.: The geometry of arc interruption. Gen. Electr. Rev. 1941, p.207-216.

4. Boehne E.W., Schuck C.L.: Performance criteria for current limiting power fuses. Trans. AIEE 1946, p.1034-1045, 1191-1194.

5. Dołęgowski M.: Spannungsverlauf an der einfachen Lichtbogenunterbrechung in den Sicherungen mit Sandlöschung und Einengungsschmetzstreifen. Switching arc Phenomena SEP - Łódź 1970.

6. Dołęgowski M.:Gechvindigkeit der Verlangerung des Lichtbogens bei den Streifensicherungen mit Sandloschmittel. International Symp. Switching Arc Phenomena Łódź 1973.

7. Dołęgowski M.: Firing voltage tests in cut-outs with sand extingsnishing medium and necked band fuse elements. Elektrotechnika, IEl Warszawa, Biuletyn Informacyjny 1970, z.4, p.1-5.

8. Dołęgowski M.: Calculation of breaking transients of current limiting cut-outs. Doctor's thesis , Instytut Elektrotechniki Warszawa 1976 /under preparation/

9. Gruner-Nielsen B., Holm Larsen J.: Sikrungsovorspaendinger po Lanspaendingssalaeg. Ingeniren 1964, nr 18, s.455.

10. Hibner J.: Resistance gradient method of calculation of the peak value of overvoltages generated by short-circuit current limiting cut-outs. Doctor's thesis, Technical University Gdańsk, 1973.

11. Kroemer H.: Der Lichtbogen an Schmetzleitern in Sand. Arch. f. Elektr. 1942, Nr 8, s.455-470.

12. Lipski T., Zimny P.: Eine Beitrag zur Berechnung des Joulischen Lichtbogen intergrals und der Ausschalterbeit von Strombegrenzeden Schmelzsicherungen. E und M, 1972, Nr 11, s.461-464.

13. Lipski T.: Graphical method of determining the limited current of fuse cut-outs, PE 1963, Nr 3, s.101.

14. Mayr O.: Beitrage zur Theorie des statischen und des dynamischen Lichtbogens Arch. f. Elektr. 1943, Nr 12, s.588-608.

15. Meyer G.J.: Zur Theorie der Aschmelzsicherungen Munchen 1906.

16. Vermij L.: Electrical behaviour of fuse elements. Dissertation T.H. Eindhoven 1969.

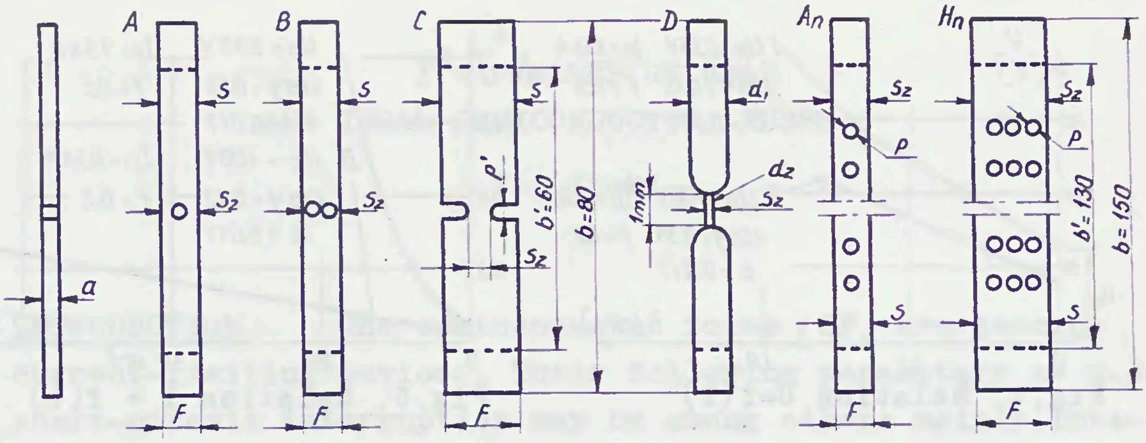

Fig.1. Shapes and dimensions of fuse elements of band type A,B,C, A_n, H_n and of wire type D.

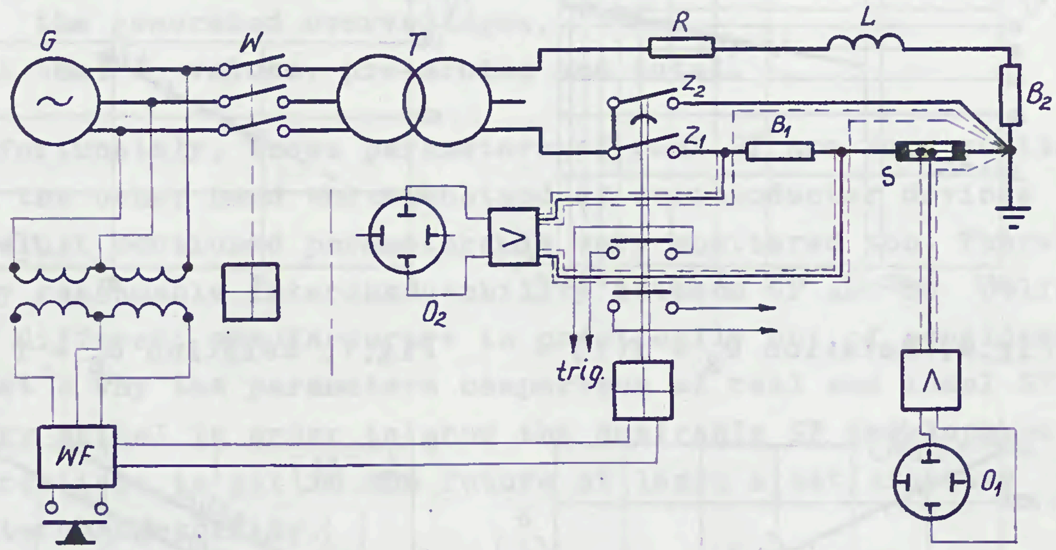

Fig.2. Test circuit for testing cut-outs by the arcing stoppage method. B_1 - tested cut-out, B_2 - auxiliary cut-out.

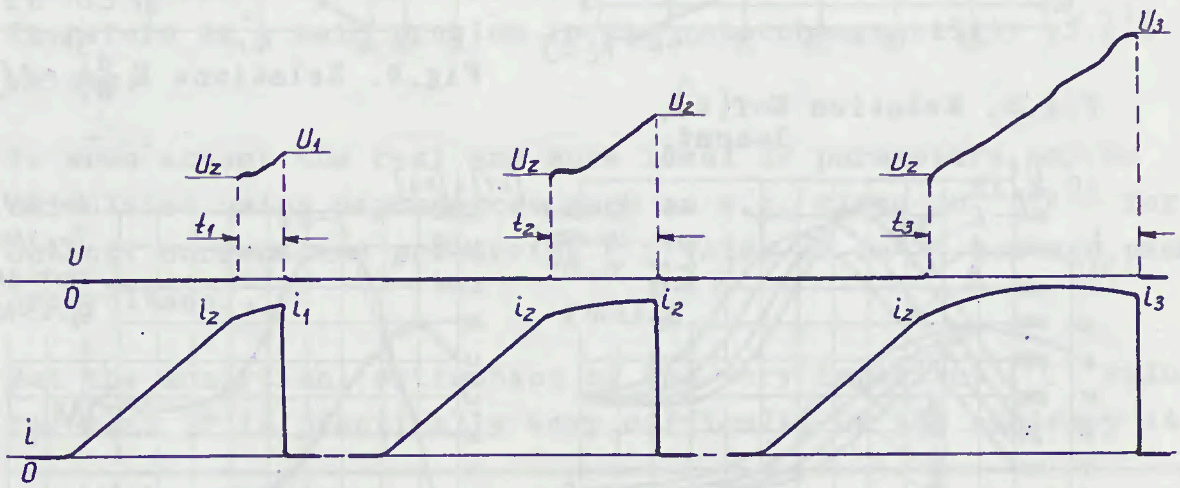

Fig.3. Successive oscillographic records from tests of a series of cut-outs. $U_{1...3}$, $i_{1...3}$ - voltage and current at moment of arcing stoppage.

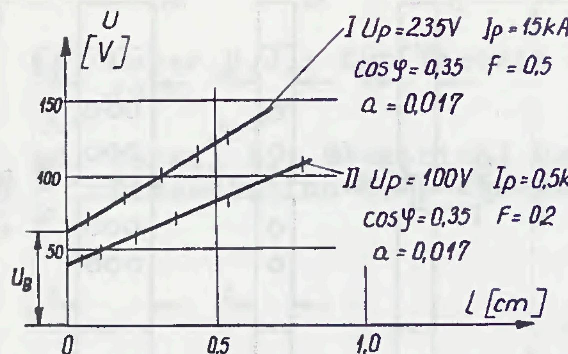

Fig.4. Relation U=f(l)

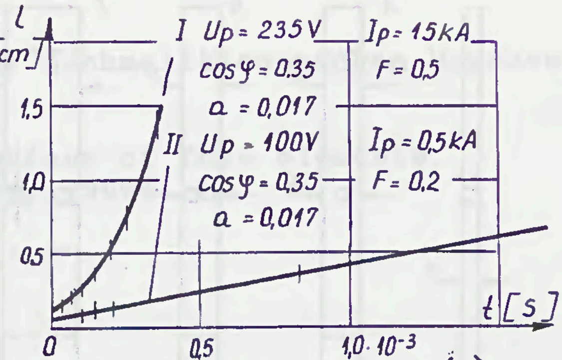

Fig.5. Relation l = f(t)

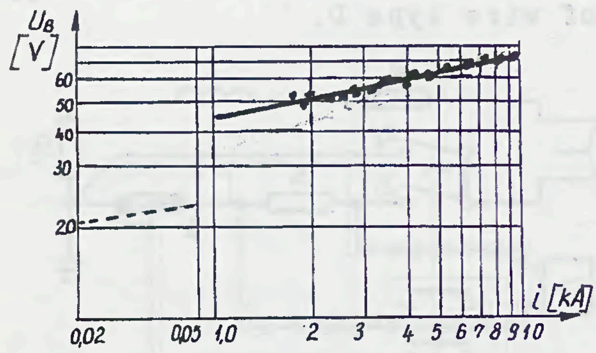

Fig.6. Relation $U_B = f(i)$

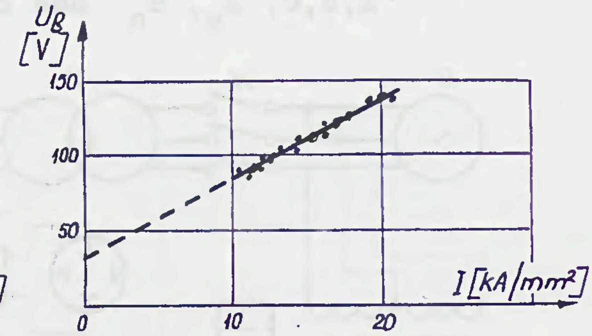

Fig.7. Relation $U_B = f(i/s)$

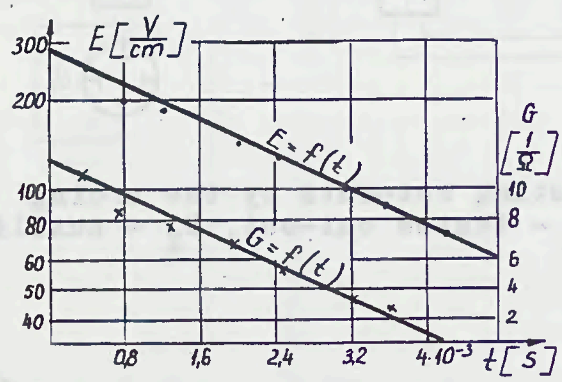

Fig.8. Relation E=f(t),
l=cont.

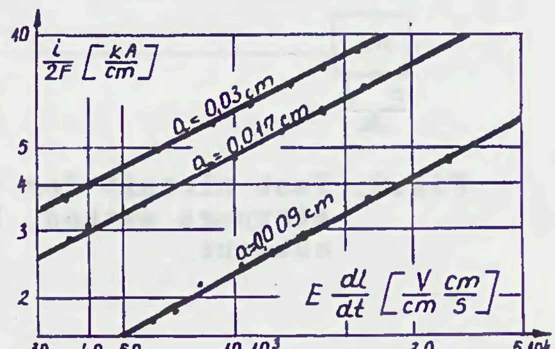

Fig.9. Relations $E\frac{dl}{dt} = f(\frac{i}{2F})$

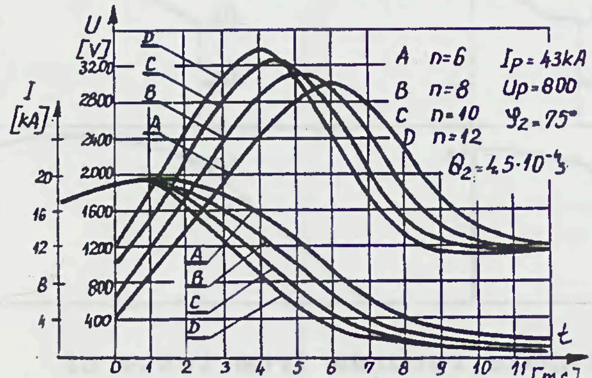

Fig.10. Calculation example of voltage and current transient.

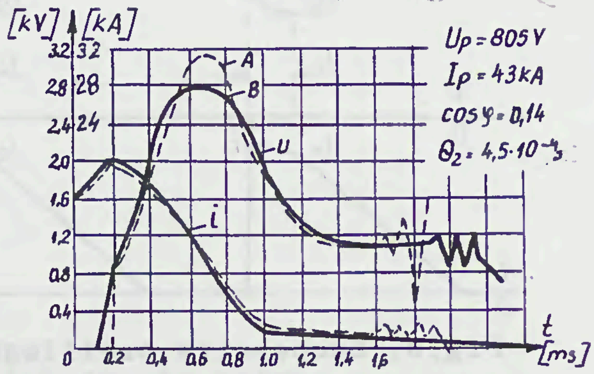

Fig.11. Voltage and current transients.A-calculated B-actual.