SIMULATION OF SHORT CIRCUIT TESTING OF HIGH VOLTAGE FUSES

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INTRODUCTION

A method for simulating the performance of a fuse is of great value to fuse designers by reducing expensive development tests. At present the main problem to achieve this, is the quality of the physical models of fuse behavior.

In this paper results from simulation of high voltage fuse performance are discussed. The simulation is mainly based on a physical model recently published by J. Daalder [1].

An interactive simulation program for computing current, arc voltage and arc energy input for fuses tested in an IEC-type test circuit has been developed. The program is written in FORTRAN 77 and runs on a minicomputer with graphic terminal.

The computations starts when a making switch S, figure 1, is closed and stops when the current reaches zero. The simulation covers the prearcing and the arcing period, and it is applicable for currents where the prearcing heating of the fuse element is essentially adiabatic.

$$\frac{di}{dt} = \frac{u(t) - R \cdot i - u_F}{L} \qquad (1.1)$$

where: $u(t)$ - source voltage
R - source resistance
L - source inductance
i - circuit current
u_F - total fuse voltage

PHYSICAL ARC MODEL

In a recent report Daalder [1] describes a model for the arc voltage in a high voltage fuse. An arc with a rectangular cross section is considered. Based on Wheeler's [2] theory the field strength in the arc can be written:

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$$E = 0.034 \cdot (Z\ln\Lambda)^{0.4} \frac{i^{0.4}}{b^{0.4} \cdot D} \qquad (2.1)$$

b is the width of the fuse element and D is the thickness of the arc channel. According to Wheeler [2] $Z\ln\Lambda$ has a value between 5 and 10 for most experimental plasmas, while Daalder [1] has found that $Z\ln\Lambda = 11.5$ gives the best result in his experiments.

The arc channel thickness D is given by:

$$D = \sqrt{(D_0')^2 + B \cdot t} \qquad (2.2)$$

where D_0' is the initial thickness of the arc channel and B is given by:

$$B = \frac{0.034 \cdot [Z\ln\Lambda]^{0.4} \cdot \gamma \cdot (1-\rho_s/\rho_1)}{b^{1.4} \cdot H} \cdot i^{1.4} \; [m^2/s] \qquad (2.3)$$

ρ_s and ρ_1 is the spesific mass of quartz sand in solid and liquid state respectively. H is the energy necessary to raise the temperature in the sand beyond the fusion temperature. A factor γ is introduced to describe to what extent the molten silica flows into the voids of the sand. It has been experimentally established that H/γ is constant.

The single side burn back rate for a given current density, j, is:

$$v = \frac{j \cdot U_{con}}{H} \qquad (2.4)$$

where U_{con} is the power loss per ampere arc-current. H is the total entalphy of the fuse element per unit volume.

NUMERICAL MODEL

Prearcing period. When computing the prearcing current the voltage across the fuse element is neglected. Equation (1.1) can then easily be solved:

$$i(t) = \frac{u(t)}{|Z|} (\sin(\omega t + \omega t_1 - \varphi) - \sin(\omega t_1 - \varphi) \cdot e^{-t/\tau}) \qquad (3.1)$$

where: $\varphi = \arctan \frac{\omega L}{R}$

$\tau = L/R$

$Z^2 = R^2 + (\omega L)^2$

t_1 = time corresponding to making angle

ω - angular frequency

It is assumed that the parallel fuse elements share the circuit current equally, and that all the notches disintegrates simultaneously. The moment of arc initiation is found by solving the equation for the melting integral.

Arcing period. After arc initiation equation (1.1) cannot be solved analytically. A second order Runge-Kutta method is used to solve the equation. The current is then given by:

$$i_{n+1} = i_n + (K1 + K2)/2 \tag{3.2}$$

where K1 and K2 are the Runge-Kutta parameters.

The total fuse voltage, u_F, is computed in a separate program unit.

The burn-back rate is given by equation (2.4), and the length of a single arc can then be found:

$$l_{n+1} = l_n + v \cdot \Delta t \cdot 2 \tag{3.3}$$

The channel thickness, $D_{x,n+1}$, in position x, figure 2, is given by:

$$D^2_{x,n+1} = D^2_{x,n} + B \cdot \Delta t \tag{3.4}$$

$D_{x,n+1}$ must be computed for all positions x along the channel. Figure 2 shows the asymmetric part of the arc channel in the way it is represented in the simulation.

u_F is given by equation (3.5) when l_{n+1} and $D_{x,n+1}$ is known:

$$u_F = m \cdot \sum_{x=1}^{k} 0.034 \cdot [Z\ln\Lambda]^{0.4} \frac{(i_n/p)^{0.4}}{D_{x,n+1}} \cdot \Delta x \cdot 2 + m \cdot 15 \tag{3.5}$$

where: $2k = l_{n+1}/\Delta x$ is an integer, p is the number of parallel conductors in the fuse, m is the number of notches.

The last term in equation (3.5), representing the electrode voltage fall, is reduced to 2·15 when the burn back is completed.

COMPUTER PROGRAM

The program is interactive and it is easy for the user to make changes in the input data. The following data can be spesified by the user:

- Physical data of the fuse element
- Quartz average grain size
- Physical data for quartz sand
- Model parameters ($Z\ln\Lambda$, H/γ)
- Prospective current

- $\cos\varphi$ for the test circuit
- Making angle
- Time step (Δt)

The parameters R and L in the test circuit will automatically be calculated when prospective current and $\cos\varphi$ has been spesified.

Current and arc voltage is presented as curves on a graphic monitor. Curves from the last simulation is stored on a file, so that results from different simulations can be compared. The program also computes the total energy input into the fuse, maximum arc voltage, prearcing time and arcing time.

RESULTS

Data for 12 kV/40 A -and 36 kV/40 A -fuses have been used as input in the program for computation of current and arc voltage. The computed curves are compared with oscillograms from I1 and I2 certification tests for these fuses. The oscillograms, which are fed into the computer with relatively rough resolution, are refered to as "test curves".

Figure 3 and 4 show computed currents and arc voltages compared with the test curves using the values for D_0' and B purposed by Daalder [1] . The source voltage is included in fig. 4 a). There is a considerable discrepancy between the two sets of curves. It is evident that the simulation model gives too high values for initial arc voltage, and too low values for the maximum arc voltage. The discrepancies in arc voltage leads to a profound difference between simulated and measured currents.

The weaker points of the simulation model are supposed to be the estimates of B and D_0' , as these parameters are based on empirical results and, to some extent, relatively rough physical models. For these reasons the effects of varying B and D_0' are studied (fig. 5 and 6).

The quartz grain size, and thus D_0', effects the initial arc channel thickness. An increase in B has the desirable effect of reducing the initial arc voltage, but a large B leads to a slower arc voltage raise and a reduced maximium voltage. The latter effects tends to increase the difference between the simulation model and the real fuses.

The discrepancies between the calculated curves and the test curves can be greatly reduced by altering the values of B and D_0' as compared to those purposed by Daalder [1]. Figure 7 and 8 show results from simulation with adjusted values. It should be pointed out that these values of B and D_0' improves the results both for I1 and I2 test simulation.

There is no strong evidence, neither theoretical, nor experimental that the parameters D_0' and B really are constants during the entire arcing period.

An improved conformity between calculated and measured currents and voltages could be obtained by making D_0' and B slightly time dependant functions.

It seems likely that D_0' is larger during the disintegration of the notches than it is during the burn-back period. The expansion rate of the channel possibly decreases as the channel grows. This would imply that B are gradually reduced during the arcing period.

These changes in the simulation model would cause a lower intial arc voltage, a steeper voltage curve in the arcing period before the maximum value is reached, and a reduced rate of voltage decrease in the last part of the arcing period.

CONCLUSIONS

A simulation model describing the behaviour of high voltage fuses during the breaking period based on presently available physical models of arcs in quartz sand has been made.

There is a reasonable conformity between the experimental and the calculated curves when the parameters for the initial arc channel thickness and the arc channel expansion rate are adjusted. The experience with the model is, at present, not sufficiently extensive to evaluate the usefulness of the simulation model for fuse designers.

The simulation results indicate that the purposed constants in the expression for the arc channel expansion rate and initial thickness may be dependant on time.

REFERENCES

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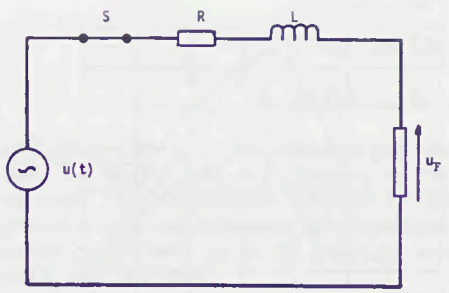


Fig. 1. Test circuit

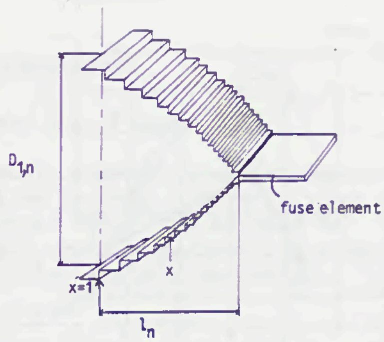
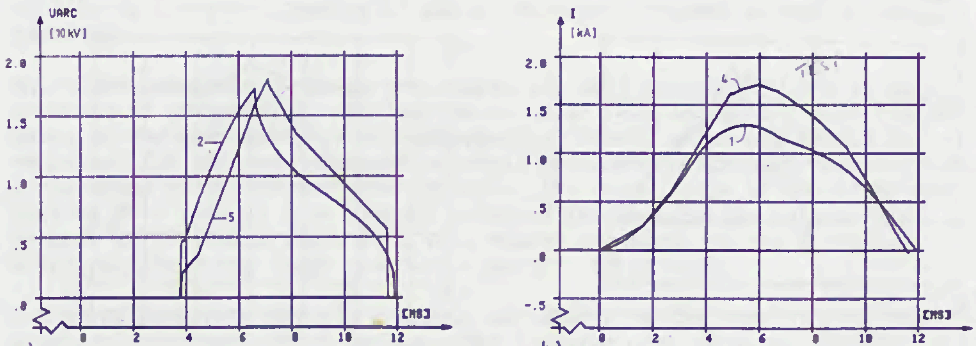
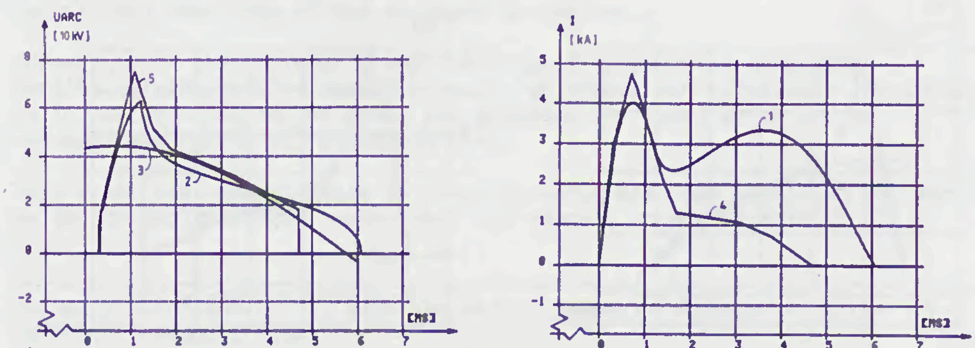


Fig. 2. "Numeric" arc channel.



a) b)

Fig. 3. 12 kV/40 A. I2-test. $B=3{,}25\cdot10^{-8}\cdot i^{1{,}4}\ m^2/s$, $D_0' = 0{,}14$ mm
a) Arc voltage. (2) Computed curve, (5) Test curve
b) Current. (1) Computed curve, (4) Test curve



a) b)

Fig. 4. 36 kV/40 A. I1-test. $B=3{,}25\cdot10^{-8}\cdot i^{1{,}4}\ m^2/s$, $D_0' = 0{,}14$ mm
a) Arc voltage. (2) Computed curve, (5) Test curve, (3) Source voltage
b) Current. (1) Computed curve, (4) Test curve

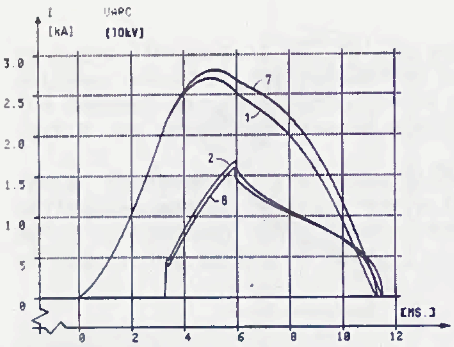


Fig. 5. Influence of D_o'.
12 kV/63 A. I2-test.
(1,2) D_o' =0,14 mm, (7,8) D_o'=0,22 mm

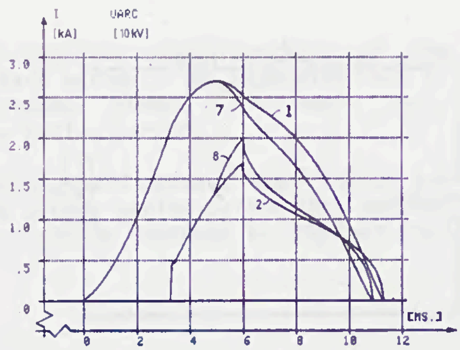
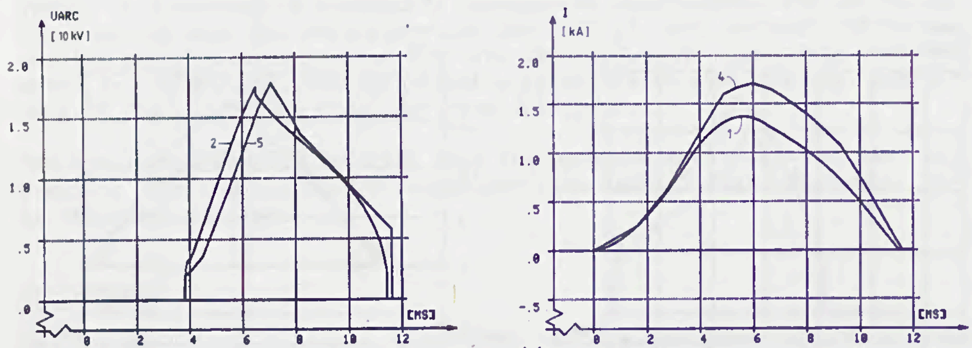
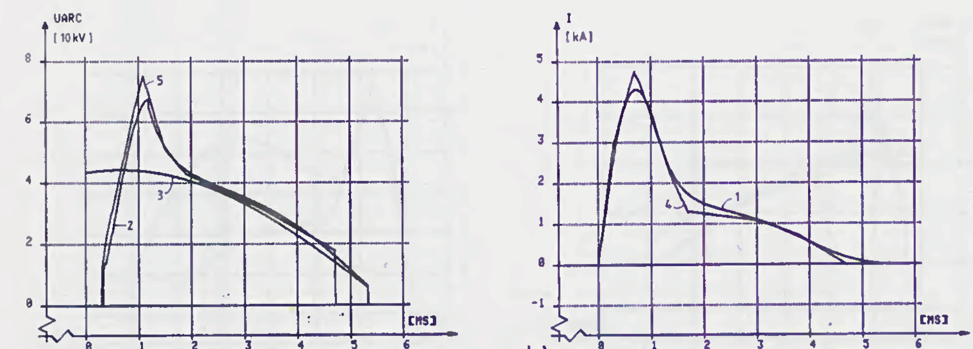


Fig. 6. Influence of B. 12 kV/63 A.
I2-test. (1,2) B=3,25·10^{-8}·i^{1,4} m^2/s.
(7,8) B=1,62·10^{-8}·i$^{1.4}$ m^2/s.



a)
b)

Fig. 7. 12 kV/40 A. I2-test. B = 1,62·10^{-8}·i^{1,4} m^2/s, D_o' =0,22 mm
a) Arc voltage. (2) Computed curve, (5) Test curve
b) Current. (1) Computed curve, (4) Test curve



a)
b)

Fig. 8. 36 kV/40 A. I1-test. B = 1,62·10^{-8}·i^{1,4} m^2/s, D_o' =0,22 mm
a) Arc voltage. (2) Computed curve, (5) Test curve, (3) Source voltage
b) Current. (1) Computed curve, (4) Test curve