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MODEL OF WARMING AND BREAKING OF FUSIBLE FILAMENTS IN HIGH VOLTAGE FUSES

Árpád BOKOR and Gábor GONDA

Department of Electromagnetic Theory
Technical University of Budapest
H–1521 Budapest, Hungary
Fax: + 36 1 166–6808, email: bokor@evtsz.bme.hu
Phone: + 36 1 204 1111/28–19

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Abstract

The warming up, melting and warming of the melted filament with the inhomogeneous cross-section of high voltage fuses is modelled with aid of a nonlinear electrical RC-network. The arcing, breaking of the fuse is simulated as well. Great prospective current, rapid warming and breaking procedure, consequently, constant geometrical sizes during the warming are assumed.

Keywords: high voltage fuse, breaking arcing.

1. Introduction

On the fusible filaments of high voltage fuses there are short sections thinned in equal distances from each other. Three types of fusible filament applied in practice can be seen in the *Fig. 1*. (The number of the thinned sections is about 80–120.) In this report we will confine ourselves to dealing with the first one, the a) type referred as 'cylindrical' fusible filament. The two remaining types may be treated similarly.

The function of the thinned sections is to prolongate the process of the current's breaking. Applying fusible filaments of homogeneous cross-section, the breaking of the current is too rapid, thereby, extremely high voltage can arise when current is interrupted and this voltage may be dangerous for appliances protected by the fuse. The warming and melting, the warming of the melted filament and its boiling take place uniformly along the whole filament of homogeneous cross-section. The huge short circuit current is conducted by the boiling fusible filament, but all of a sudden, when the whole filament has evaporated, the current being interrupted induces very high voltage.

If the fusible filament's cross-section is not homogeneous but it has thinned sections, the process of warming, melting and boiling is not uniform along the filament. First the thinned sections will evaporate and in these places electric arc conducts the current, while the other sections of

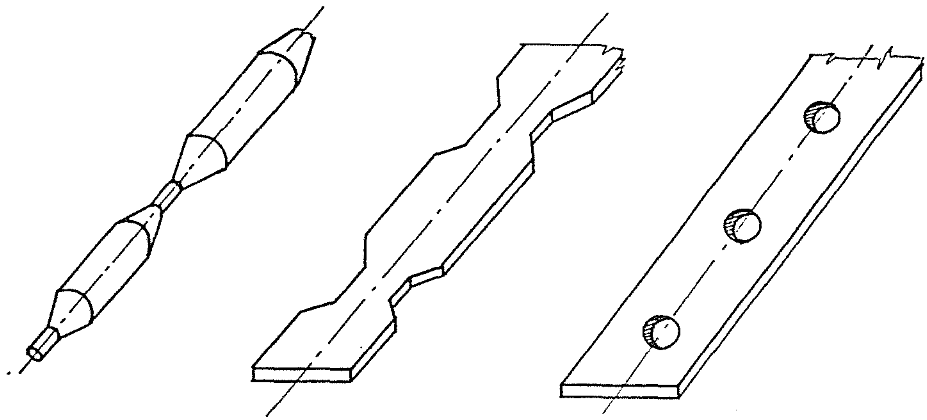


Fig. 1. Fusible filaments of different kinds

normal cross-section have far less electric resistance. These sections gradually evaporate and the length of the arcs increases. It yields a restriction or limitation in the current and the process breaking of the current will be prolongated, so the induced voltage will be far less than the one at speedier interruption of higher current.

On one hand, this prolongation is very useful preventing apperance of extremely high voltages. On the other hand, it can be disadvantageous. Because of the extreme prolongation an electric arc can develop between the two ends of the fuse that remains after the whole fusible filament has evaporated as far as the next zero transition of the voltage. So instead of some hundred μs the duration of the arcing can reach some ms-s. And the energy delivered inside the fuse from the moment of the short circuit to the end of fusing can be 10^3–10^5-times bigger than in regular fusing, when the fusible-filament having evaporated interrupts the arc and the current. It results in the explosion of the fuse. But from the practical point of view the explosion of the fuse is inadmissible. Consequently, the increase of the length of arcs must be quick enough resulting in the current interruption. The increase rate of arc length is sensitive to the length and cross-section area of the neighbouring filament parts of different cross-section.

Therefore it is clear that the appropriate construction of fusible filaments and the thinned sections on them are of great significance. Solely experimental production of fusible filaments of suitable construction is extremely expensive. That is why the modelling of current's increase in a breaking, the warming and fusing of filaments and the interruption of current are very profitable.

In a quick interruption (interesting in practice when the so-called prospective breaking current is very high) only the direct surroundings of the fusible filaments can get warmed up so it is enough to model and take just silver fusible filaments of varying cross-section and their surrounding thin sand layer are into account.

First we will describe the simulation of the warming of the filament till the moment when the thinned section in the middle of the fuse begins to evaporate, then the model of arcing till the interruption will be demonstrated.

2. Simulation of Warming to the Boiling Point

Due to the simple filament constructions, — by dividing filament and surrounding sand layer into regions, just a few types of geometrical formation have to be considered. Modelling the heat capacity of each region and thermal conduction between neighbouring regions, we get a thermal network that is analogous to an electrical RC-network.

A periodically repeating section of a cylindrical fusible filament and the RC-network analogous to it and its surroundings are shown in *Fig. 2.* Here $\tau_1, \tau_2, \ldots \tau_{12}$ represent the temperature of the centres of the single regions (they correspond to the nodal potentials in the RC-network). C_1, C_2, C_3, C_4 capacitors model the heat capacity of the 1., 2., 3., 4. region of the fusible filament section, respectively, the $C_5 - C_{12}$ are the heat capacitances of the corresponding sand layer regions. Each heat capacity can be written as

$$C_i = c\rho V_i, \tag{1}$$

where c – specific heat, ρ – specific mass-density, V_i – volume. G_1, G_2, ... G_{11} represent the heat conduction between the centres of the neighbouring regions. The formulas can be deduced from the Fourier's law of heat conduction:

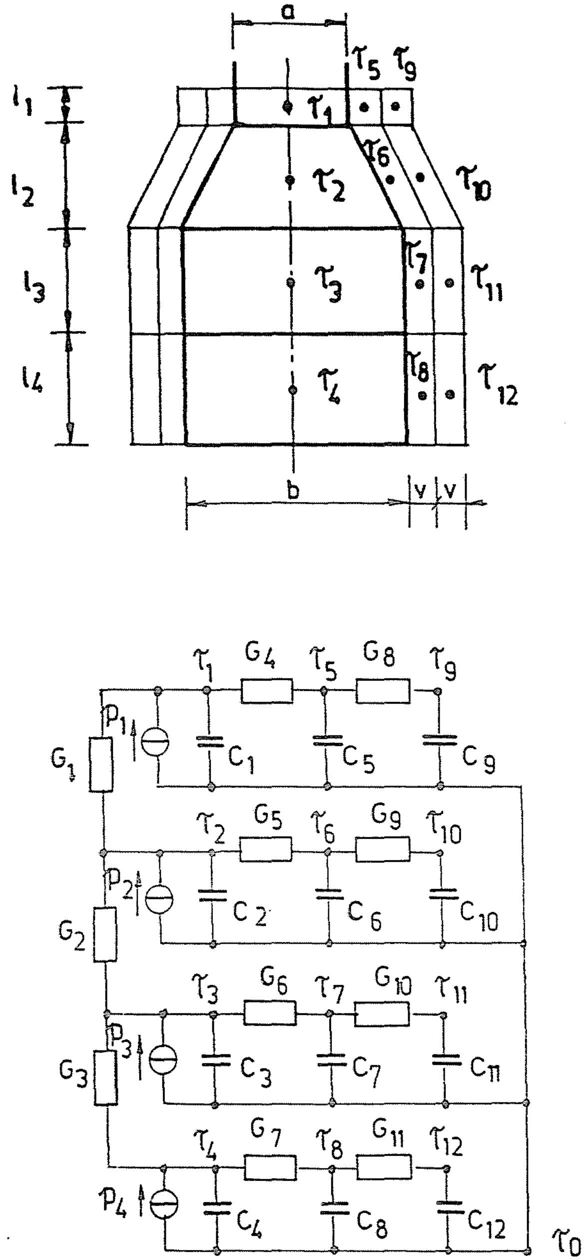
$$p = -\lambda(\text{grad } \tau)(\Delta A), \tag{2}$$

where p – heat power crossing the ΔA cross-section, τ – temperature as a space function, λ – specific heat conduction.

The heat conduction between the two ends of a special geometrical formation is defined by the

$$G = \frac{p}{\Delta\tau} \tag{3}$$

formula, where $\Delta\tau$ gives the temperature difference across the formation and p is the conducted heat power.



a.

b.

Fig. 2. One section of a fusible filament (a) and the RC-network analogous to it and its surroundings (b)

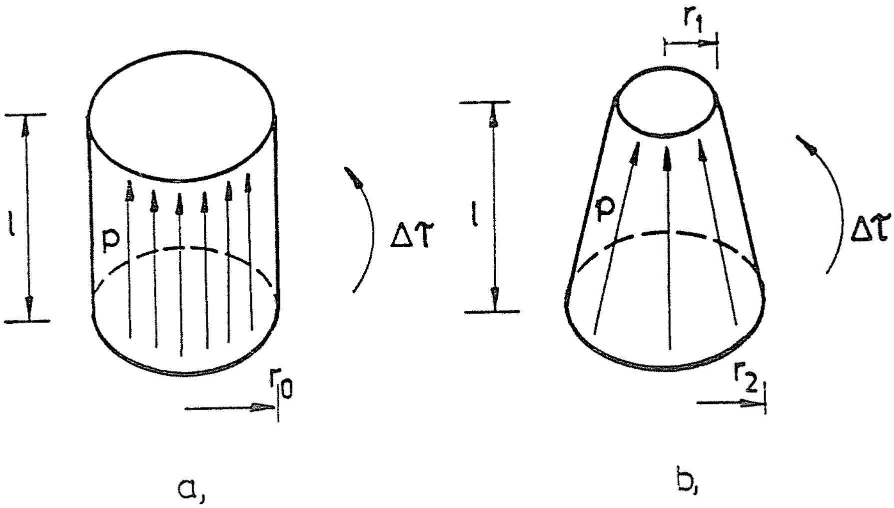


Fig. 3. Two special geometrical formations of a fusible filament

For calculating the heat conductions between the centres of the neighbouring regions (G_1, G_2 and G_3) we can use the following formulae (simply resulted from the Fourier's law of heat conduction and the definition given above). For the special formations shown in *Fig. 3a* and *Fig. 3b*, respectively:

$$G_a = \lambda_{Ag} r_0^2 \pi / l \ , \tag{4}$$

$$G_b = \lambda_{Ag} r_1 r_2 \pi / l \ . \tag{5}$$

In order calculate the G_4 — G_{11} heat conduction, two types of geometrical structures have to be taken into consideration. The corresponding heat conduction formulae for these formations are given by the following relation:

$$G_a = \frac{2\pi\lambda_s l}{\ln(1 + v/r_1)} \ , \tag{6}$$

$$G_b = 2\pi\lambda_s \int_0^l \frac{dx}{\ln(1 + vl/(r_2 l + (r_2 - r_1)x))} \ . \tag{7}$$

Here λ_s is the specific heat conduction of sand, the meaning of the geometrical parameters can be seen in *Fig. 4*. All of G-s parameters can be calculated on the basis of the given formulas, but we will not go into details.

So parameters of every component in the network shown in *Fig. 2.a* can be calculated according to the formulas given above with the exception

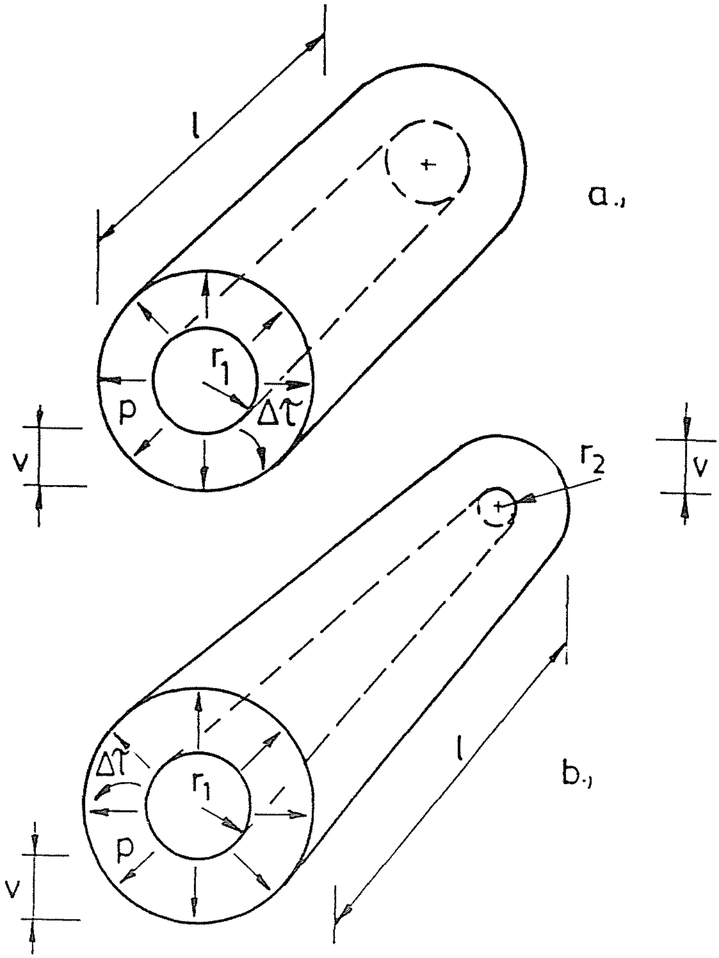


Fig. 4. Special formations for sand layer sections surrounding the filament

of heat power delivered in the fusible filament sections that are modelled by p_1, p_2, p_3 and p_4 power sources. These powers can be calculated very easily

$$p_k = i^2 R_k, \quad k = 1, 2, 3, 4, \tag{8}$$

where R_k is the temperature dependent electric resistance of the corresponding filament section, i is the current which can be calculated on the basis of the voltage–current characteristic of the embedding circuit, the source voltage in it regarded as a given time function and the resultant resistance of the fusible filament.

The nonlinear network model will be calculated by numerical integration of the state equations of the system. The method is well known, so there is no need to detail. (See e.g. FODOR, 1988).

Only one further remark: the topology of the original nonlinear network has not been changed in the whole warming process. One may think that a melted section in the further warming as a liquid medium does not keep its shape and place. But the warming process to the boiling point and the evaporation takes place so quickly that this shape modification can be neglected. (More than 14 ms is necessary for a mass point to move a distance of at least 1 mm in the gravitation field.) The duration of the boiling process is far shorter in rapid interruptions covered by our investigation.

The temperature of the fusible filament section during melting does not increase. We have taken this fact into consideration by the extremely increased heat capacitance of the melting section as if the specific heat c in (1) would be infinite. Consequently, the topology of the network has not been changed in the melting process.

The diagram in *Fig. 5a* shows the result of a calculation when the voltage across the fuse has increased according to a sine wave time function of 50 Hz. The 1, 2, 3 and 4 curves concern the centre points of the fusible filament sections (see *Fig. 2a*). At this very rapid procedure the temperature of the narrowest section reaches the boiling point while other parts of normal cross-section do not even reach the melting point, and the temperature of its neighbouring sand region just begins to increase (curve 5). The result in the *Fig. 5b* applies to a different filament construction (the thinned section has larger measurement and mass) but the embedding network and the voltage across the fuse were not changed. Here the parts of normal cross-section have been melting when the narrowest section begins to boil.

3. Arcing Simulation

The current-voltage characteristic of the electric arc was taken into account by an arbitrarily assumed formula

$$u_a = A + Bh + (C + Dh)/i_a \ , \tag{9}$$

where u_a – the voltage across the arc, i_a – arc current, h – arc length, A, B, C, D constant values established empirically for a given type of fuse. (A similar formula for the characteristic of electric arc is recommended by WALZUK (1970).) The length of the arc in one elementary part of the filament is regarded as proportional to the evaporated mass. The total electric power dissipated in one region is taken into account as the one

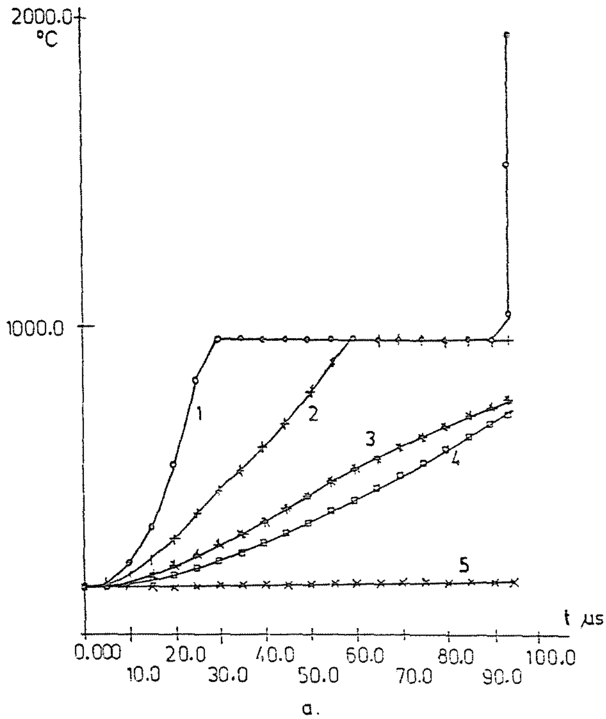
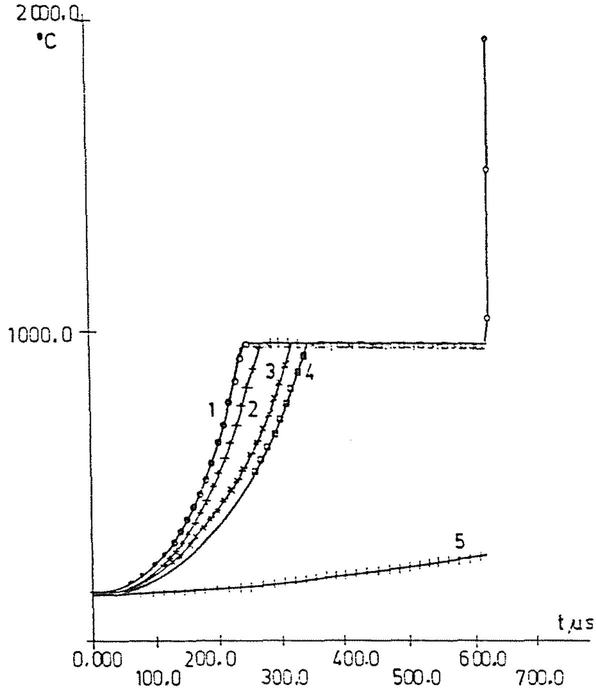


Fig. 5a. The warming of a filament section and the surroundings

producing vaporization, the energy radiation into the neighbouring sand regions is neglected.

During the arcing process the voltage dropping along the other parts of the filament is negligible compared to arc voltages, so the resultant voltage–current characteristic for the filament is similar to (9), as the current is common, the voltage across the filament is the sum of the voltages of the arcing sections. Consequently, in the formula analogous to (9) for the whole filament, nA stands instead of A, nC instead of C and $\sum_{i=1}^{n} h_i$ instead of h. (n – the number of boiling sections, h_i – the length of i-th boiling section, $i = 1, 2, \ldots n$.)

The geometrical construction of a filament is periodical: the lengths of small and normal cross-sections are equal, but in the warming process they are at different states. (The different parts of the filament have different initial temperatures.) Consequently, the arc length is not of the same value for the different periods of the filament. The exact modelling of the warming separately for any filament period would make the calculation



b.

Fig. 5b. The warming of a filament section and the surroundings

too complicated. The warming, melting and arcing process is simulated for only a single filament period. The arc length for the other periods is estimated on the basis of the formula scalled Joule integral, that is

$$J(t) = \int_0^t i^2(\vartheta)\mathrm{d}\vartheta \tag{10}$$

(t – time, $i(\vartheta)$ – current–time function), which is calculated and stored as well together with other data (temperature, arc length) during the simulation process. Then for the sections of common geometrical parameters in different filament periods the same Joule integral value (starting from the same temperature) results in the same arc length.

As the resultant characteristic is changing in the arcing process it may become inconsistent with the one of the embedding circuit. It means the breaking of the current. *Fig. 6* shows the current–time function for such an interruption when the current is broken in spite of the increasing voltage. The filament has not been fully evaporated yet. The construction of the

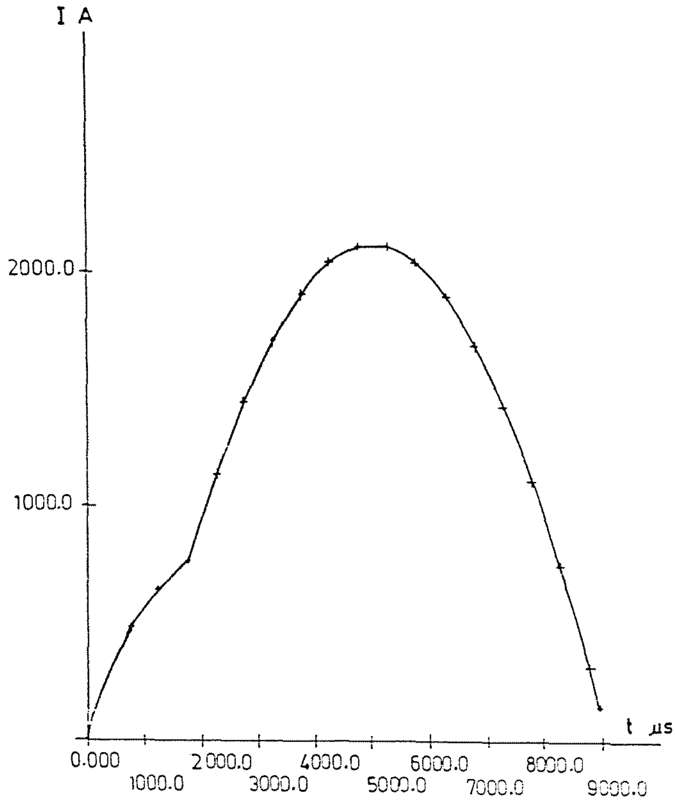


Fig. 6. Current-time function in a proper fusing

filament is satisfactory when the interruption takes place not just because of the zero transition in voltage but the rapidly increasing arc length results in a modified increase, then a gradual decrease of the current. Consequently, both the evaporation of the fuse and a huge voltage induction when current is interrupted are avoided. (We must remark in connection with *Fig. 6* that in our model a sinusoidally increasing voltage is assumed. In real circumstances, because of the voltage dropping through the embedding circuit components, the very small part of this voltage falls to the fuse resulting in a quite different current shape.)

4. Conclusion

The numerical results (e.g. the warming, melting and breaking duration depending on the prospective breaking current, and so on) are supported by the measurment results got in certification test of fuses. This calculation is easily repeatable at different voltage functions across the fuse, at different modifications of fusible filament. This modelling and calculation make the optimization of the fusible filaments much more economical.

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