CURRENT-LIMITING CAPABILITY AND ENERGY DISSIPATION OF HIGH-VOLTAGE FUSES

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INTRODUCTION

Important characteristics of a fuse are amongst others:

- the nominal current
- the energy dissipation under nominal conditions
- the current-limiting capability (cut-off characteristic).

These basic characteristics are determined partly by the same parameters, such as e.g. the cross-section and the length of the fuse-element, physical parameters of the material of which the fuse-element is composed, the mechanism of the heat transfer from the fuse-element to its surroundings, the maximum permissable temperatures, etc. That means that the above mentioned basic characteristics are not independant from each other. The aim of this paper is to show the relationship existing between the energy dissipation under nominal conditions P_n on the one hand and the nominal current I_n and current limiting capability or cut-off current I_c on the other hand.

Two situations will be studied, viz.

- fuse-elements consisting of a long, homogeneous conductor of constant cross-section (long fuse-element).
  In this case the heat generated in the fuse-element under steady-state conditions will be transported to its surroundings mainly in radial direction.
- Fuse-elements consisting of a number of short fuse-elements connected in series. In this case the heat generated in each short fuse-element is mainly transported (by metallic conduction) to the ends (heat sinks) of each short fuse-element.

It is believed that the majority of practical designs may be considered to be bounded by these two situations.

THEORETICAL CONSIDERATIONS

The energy-balance of a current-carrying fuse-wire under steady-state conditions, that means if $\partial T/\partial t = 0$, is given by:

$$\lambda \frac{d^2T}{dx^2} + J^2\rho_0(1+\beta T) - GT = 0 \qquad (2.1)$$

where $T(x)$ is the temperature at a place x (see Fig. 1), J is the current density $[Am^{-2}]$, λ is the heat conductivity of the wire-material $[W.m^{-1}.K^{-1}]$, ρ_0 is the specific resistance at ambient temperature $[\Omega m]$, β is the temperature coefficient of the specific resistance $[K^{-1}]$ and G is the total heat flux per unit length and per degC in radial direction to the surroundings of the conductor $[W.m^{-3}.K^{-1}]$. The value of G can be determined experimentally for a given case [1].

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Eq. (2.1) is valid for a conductor with length $L = 2\ell$ connected to two metal blocks (see Fig. 1) having a heat capacity which is large compared with the heat capacity of the conductor.
Introducing the boundary conditions $\frac{dT}{dx} = 0$ at $x = 0$ and $T = 0$ at $x = \pm \ell$, it can be derived that

$$T(x) = \frac{b}{a} \left[\frac{\cos x \sqrt{a/\lambda}}{\cos \ell \sqrt{a/\lambda}} - 1 \right] \quad (2.2)$$

where $a = J^2 \beta \rho_0 - G > 0$
$b = J^2 \rho_0$

In the case of short fuse-elements, where the heat transfer from the fuse-element is mainly determined by heat conduction to the ends of the fuse-element, it can be shown that $J^2 \beta \rho_0 \gg G$ [1]. Further, the maximum temperature T_m will exist at $x = 0$. So, in this case of short fuse-elements we obtain:

$$T_m = \frac{1}{\beta} \left[\frac{1}{\cos \alpha \ell} - 1 \right] \quad (2.3)$$

where

$$\alpha = J \sqrt{\frac{\beta \rho_0}{\lambda}}$$

In the case of long current-carrying conductors, the maximum temperature T_m is not influenced by axial heat transfer to the ends of the conductor. So then we have

$$T_m = -\frac{b}{a} = \frac{J^2 \rho_0}{G - J^2 \beta \rho_0} \quad (2.4)$$

Introducing the melting temperature T_s and assuming $T_m = T_s$, the equations (2.3) and (2.4) give an expression for the minimum fusing current density J_s for short and long fuse-wires respectively. From eq. (2.3) it can be seen that J_s depends also on the length $L = 2\ell$ of the fuse-element. This dependency is shown graphically in Fig. 2 for the metals Ag, Al and Pb. From eq. (2.3) and (2.4) also the ratio $q = T_m/T_s$ can be computed as a function of the ratio $p = J/J_s$. The results are given in Fig. 3 for short and long fuse-wires respectively.

The energy dP generated in a small part dx of a fuse-element with cross-section A can be written as

$$dP = J^2 \rho_0 \left[1 + \beta T(x) \right] A \cdot dx$$

Introducing eq. (2.2), assuming $J^2 \beta \rho_0 \gg G$ and integrating over the entire length $L = 2\ell$, one can derive for the total energy P generated in a short fuse-element:

$$P = 2 \sqrt{\frac{\lambda}{\beta \rho_0}} \cdot A \cdot J \cdot \rho_0 (1 + \beta T_m) \sin \alpha \ell \quad (2.5)$$

For the current I holds: $I = J \cdot A$. Further, $T_m = qT_s$ $(q < 1)$ can be introduced. If nominal current conditions are considered, for which $I = I_n$, $\alpha = \alpha_n$, $q = q_n$ and $P = P_n$ are valid, we get

$$P_n = 2\sqrt{\frac{\lambda}{\beta \rho_0}} \cdot I_n \cdot \rho_0 (1 + q_n \beta T_s) \sin \alpha_n \ell \qquad (2.6)$$

The value of q_n belongs to a value $p = p_n = J_n/J_s < 1$. These values of q_n and p_n can be derived from Fig. 3a for different metals.
From eq. (2.3) it is clear that $\cos\alpha\ell$ and consequently also $\sin\alpha\ell$ depends only on β and T_m. So under nominal current conditions, where $T_m = q_n T_s$, the factor $\sin \alpha_n \ell$ is a constant. That means that P_n according to eq.(2.6) seems to be independant of the length of the fuse-element, but depends only on q_n (or p_n), and on the physical parameters β and T_s. This conclusion, which has been confirmed by experiments, is valid as long as the radial heat transfer from the fuse-wire may be neglected, as is the case for short fuse-elements.

The energy dissipation of a <u>long</u> current-carrying conductor, for which it is assumed that its temperature T equals T_m over its entire length (this leads to a conservative estimate), can be written as

$$P_n = J_n^2 \rho_0 (1 + \beta T_m) A.L$$

where L is the total length of the conductor.
Substituting $I_n = AJ_n$ and $T_m = q_n T_s$ and introducing eq.(2.4) for $J=J_n$, we obtain

$$P_n = L I_n \sqrt{q_n T_s G \rho_0 (1 + q_n \beta T_s)} \qquad (2.7)$$

In this case the energy dissipation P_n does depend on the length of the conductor L, as would be expected.

Under short-circuit conditions the behaviour of a fuse-element can be fairly well described with Meyer's relation

$$\int_0^{t_s} J^2 dt = C_M$$

where t_s is the melting time and C_M represents Meyer's constant which is determined by physical constants of the material of the fuse-element. Defining the action integral

$$K_M = \int_0^{t_s} i^2 dt \qquad (2.8)$$

where i is the instantaneous value of the current flowing through the fuse-element, it follows with $i = AJ$:

$$K_M = A^2 C_M \qquad (2.8a)$$

The cut-off current I_c can be computed from the above equations by computing the value of i at $t = t_s$. The value of the minimum fusing current I_s and, at a given A, also the value of J_s depends on the length of the fuse-element, as demonstrated with Fig. 2.
If for a short fuse-element $I_s = A_s J_s$ is valid, and for a long fuse-element $I_{s\infty} = A_\ell J_{s\infty}$, and we require $I_s = I_{s\infty}$, then it follows that

$$\frac{A_\ell}{A_s} = \frac{J_s}{J_{s\infty}}$$

where A_ℓ and A_s are the cross-sections of long and short fuse-elements respectively.
In the foregoing it is shown that, keeping I_s constant, the cross-section can be reduced if the length of the short fuse-element is reduced. Reducing the cross-section means, however, a reduction of K_M according to eq. (2.8a) and, consequently, a reduction of I_c. So, also the ratio I_c/I_s or I_c/I_n can be reduced by reducing the length of a short fuse-element.

With the help of the above theoretical considerations it is possible to find a relation between the energy-dissipation P_n, the cut-off current I_c and the nominal current I_n of a fuse under a variety of conditions. This will be the subject of the next section.

<u>COMPUTATIONAL RESULTS AND CONCLUSIONS</u> The above mentioned relationship between P_n, I_c and I_n has been computed for long fuse-wires and, neglecting the energy transfer in radial direction, for short fuse-wires.

Assuming a certain cross-section A which is constant over the entire length of the fuse-wire, it is possible to compute the nominal current I_n of long fuse-elements from eq. (2.4) for a given metal, after introducing values for $q_n = T_m/T_s$ and G. With the same parameters the energy dissipation per unit length P_n/L can be computed from eq. (2.7), as well as the value of the action integral K_M according to eq. (2.8). If the current i in eq. (2.8) is assumed to be a symmetrical sine-wave current with peak value $\hat{I}$, a value of I_c can be found with the chosen parameters. Fig. 4 and 5 show results of such computations for long silver wires and long sodium wires respectively. Experimental evidence suggests that for G a value of $2 \times 10^6 W.m^{-3}.K^{-1}$ has to be taken, which value has been introduced in our computations. Further, for silver wires $q_n = 0.2$ ($T_m = 192$ degC) has been introduced, which seems to be a practical value. For sodium wires we introduced $q_n = 0.9$ ($T_m = 88$ degC).
As an example: Fig. 4 shows that a long silver fuse wire with $I_n = 200A$, subjected to symmetrical (50Hz) short-circuit currents with peak values $\hat{I} = 20kA$ and 40kA will cut the current at values $I_c = 18kA$ and 24kA respectively, providing the arc-voltage is sufficiently high. The energy dissipation in this fuse wire at $I = I_n$ will be approximately 9.5Watts/cm. Fig. 5 shows that under equal circumstances a long sodium wire with $I_n = 200A$ will cut the current at $I_c = 10kA$ and 12kA respectively. In this sodium wire the energy dissipation at $I = I_n$ amounts to appr. 8.6 Watts/cm. This example demonstrates that long sodium wires show a remarkable reduction of I_c compared with silver wires, whereas the eneregy dissipation is almost equal in both cases. If in the case of a long silver wire the value of G can be made three times larger than assumed earlier, and if we assume $q_n = 0.6$ ($T_m = 576$ degC), then the cut-off current will be almost equal to that of the long sodium wire under the above mentioned conditions. However, the energy dissipation of the long silver wire at $I = I_n$ will now amount to 30 Watts/cm.
A dramatical reduction of I_c, compared with long fuse-elements, can be obtained by applying short fuse-elements, as can be seen from a comparison of Fig. 4 and 5 with Fig. 6 and 7. The latter figures have been computed for short fuse-wires which are subjected to a short-circuit current with a peak value of 20kA. Fig. 6 shows for example that short

silver fuse-elements with L = 2mm and L = 10mm cut the current at values I_c = 2kA and I_c = 6kA respectively, if $\hat{I}$ = 20kA. Further Fig. 6 and 7 show that at I_n = 200A the energy dissipation amounts to 28 Watts per element for silver and 17 Watts per element for sodium, irrespective of the length of the fuse-element. For comparison, figures 6 and 7 show I_c as a function of P_n/L and I_n for long fuse-elements ($L \rightarrow \infty$). It turns out that the energy dissipation of short fuse-elements is in general larger than P_n at $I = I_n$ of long fuse-elements per equal length.

As a conclusion one can state that the total energy dissipation at $I = I_n$ of a chain of short fuse-elements in series is determined by the number of short fuse-elements and not by the total length of these short fuse-elements. This energy dissipation is larger and can be much larger than the energy dissipation of a long fuse wire with equal total length. In general, a fuse requires a minimum length of the fuse-element in order to be able to generate an arc-voltage which is sufficiently high. Also the required dielectric strength (resistance) after interruption of the current makes a certain length necessary. So one can state that the nominal voltage for which a fuse is designed requires a certain minimum total length of the fuse-element. Once this length is given, the minimum energy dissipation at $I = I_n$ will be obtained with a fuse-element which consists of a homogeneous conductor of constant cross-section. Improving the current-limiting capability by deviding the total required length into a number of short fuse-elements in series, which is especially desirable at high values of the nominal current, is only possible at the expense of a higher energy dissipation at $I = I_n$. In general one can state that the lower the cut-off current is, the higher the energy dissipation will be.

The value of the energy dissipation, even at high nominal currents, does not offer serious problems as long as low-voltage fuses are considered. High-voltage fuses, however, require much greater lengths of the fuse-elements, and this will lead to much larger values of the energy dissipation. If a maximum permissable value for the energy dissipation of high-voltage fuses exists, as will be the case with built-in fuses, only small nominal currents are possible. In general, it can be stated that it is hardly possible to built high-voltage fuses with high nominal currents (hundreds of amps) and with improved current-limiting capability in accordance with present design methods, which can meet practical requirements with respect to the energy dissipation under nominal current conditions. Improvements can only be made if the arc-voltage per unit length and the dielectric strength per unit length after current-interruption can be increased. In this respect it may be remarked that research work carried out by amongst others Salge[2] and Huhn [3] , with the aim to gain more insight in the parameters influencing the arc-voltage, seems to be very important.

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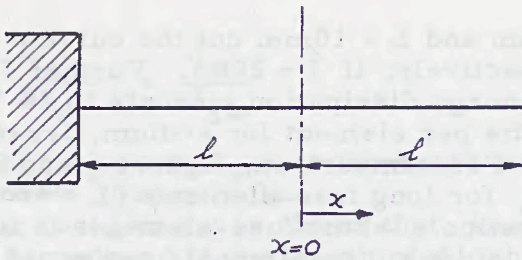

Fig. 1.

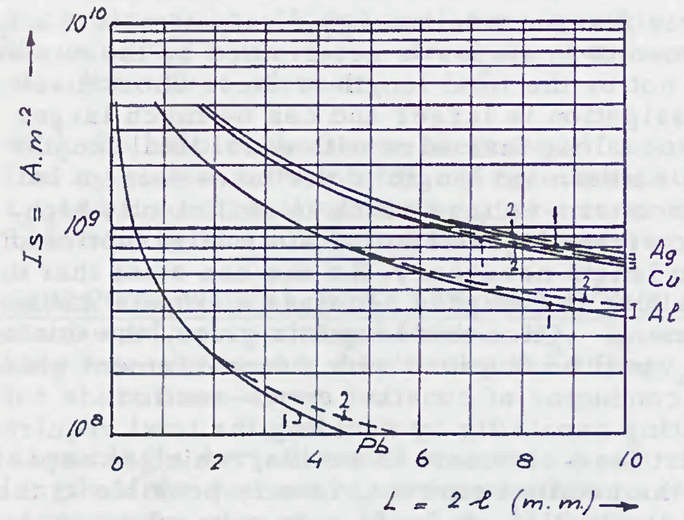

Fig. 2. The minimum fusing current density J_s as a function of the total length $L=2\ell$ of a fuse-element for the materials silver, copper, aluminium and lead. Curves 1 have been computed neglecting the radial heat transfer (G = 0) Curves 2 have been computed with $G = 6.10^6$ $W.m^{-3}.K^{-1}$.

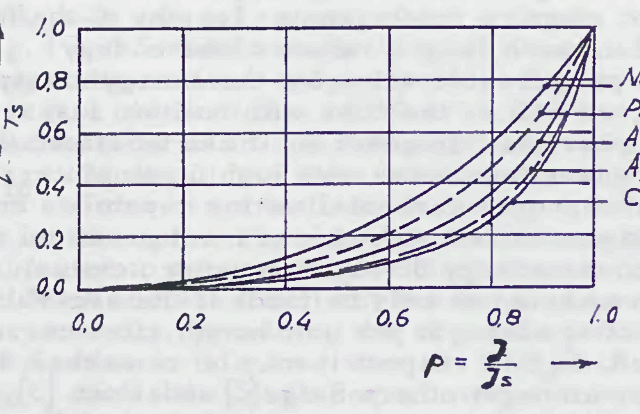

Fig. 3a. The ratio between the maximum temperature T_m and the melting temperature T_s, as a function of the ratio between the current density J and the minimum fusing current density J_s for short current carrying conductors and for the materials silver, copper, aluminium , lead and sodium.

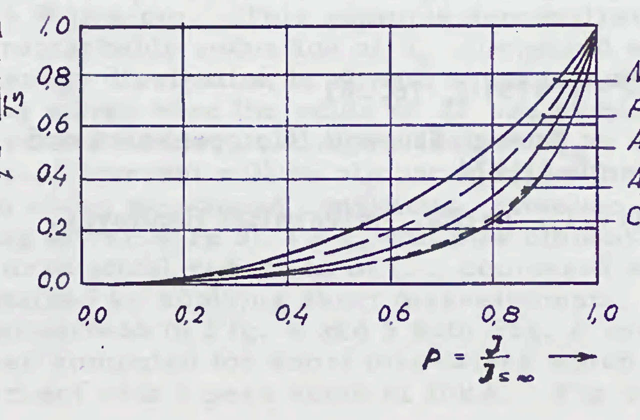

Fig. 3b. The ratio T_m/T_s as a function of the ratio J/J_s for long current-carrying conductors and for the same metals as Fig. 3a.

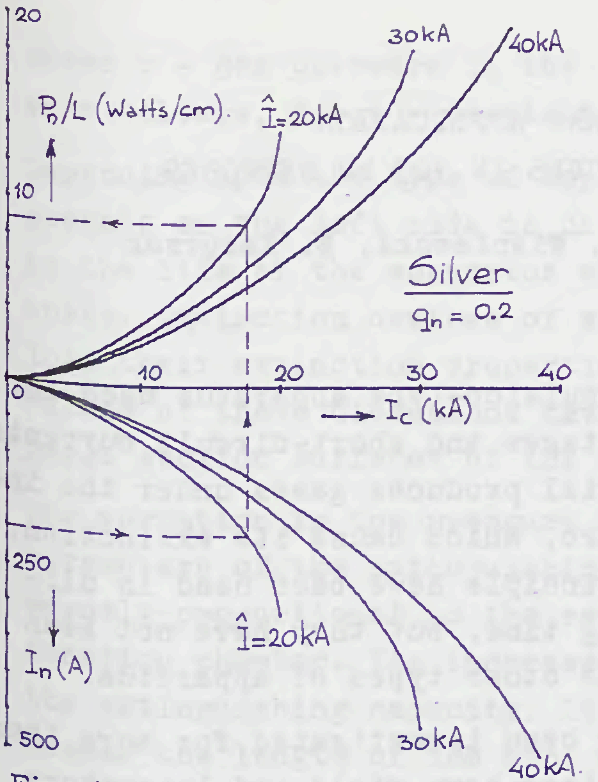

Fig. 4

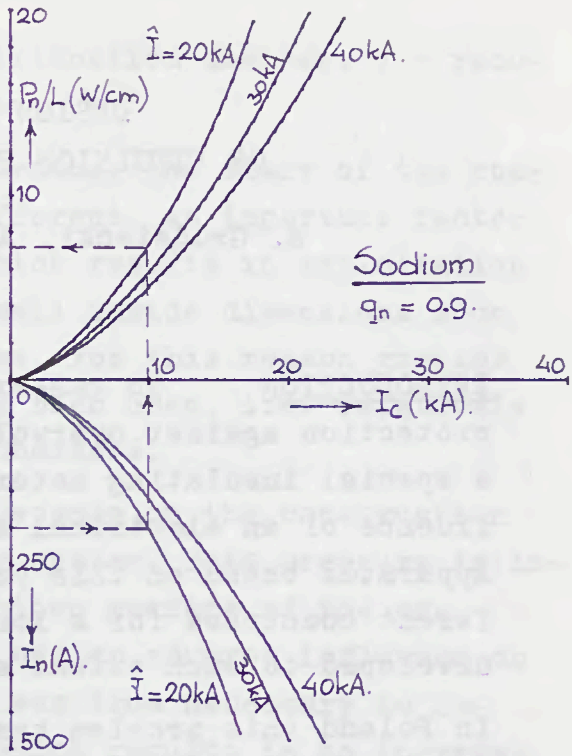

Fig. 5

Cut-off current I_c of long fuse wires (Ag and Na) as a function of the nominal current I_n and the heat dissipation per unit length P_n/L. Peak value of prospective current $\hat{I}$ is parameter.

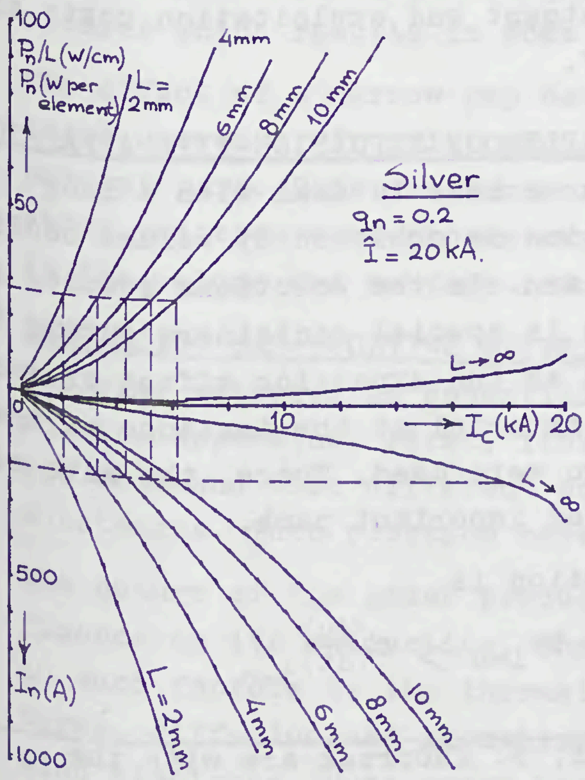

Fig. 6

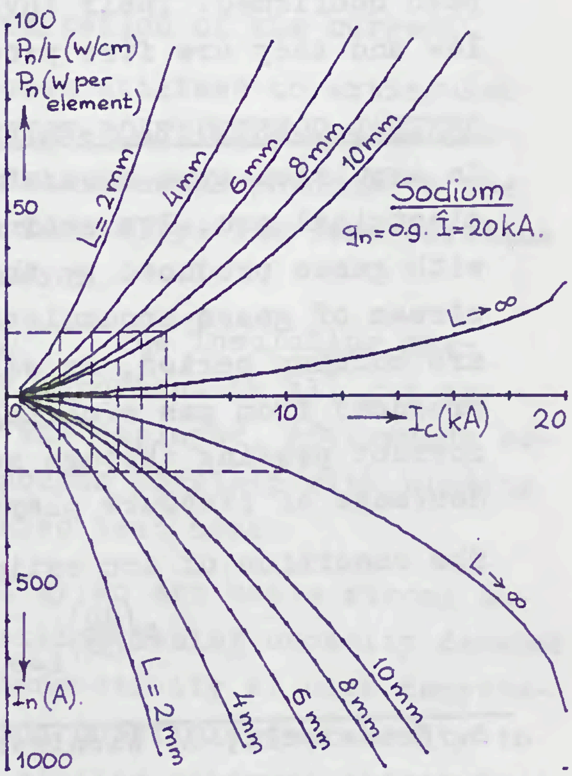

Fig. 7

Cut-off current I_c of short fuse wires (Ag and Na) as a function of I_n and P_n per short fuse-element, in a circuit with prospective current with peak value $\hat{I} = 20$ kA. Length L of short fuse-element is parameter.