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$I^2$, jumps

# NON ADIABATIC PROCESS IN FUSE ELEMENTS WITH HEAVY CURRENT FAULTS

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## Summary

The pre-arcing phenomenon in a low voltage fuse operation in the case of high values of short-circuit current is analyzed in order to evaluate relevant quantities as pre-arcing time, cut-off current and pre-arcing $I^2t$. The phenomenon is faced both by a numerical simulation of the melting element and by an experimental investigation on different types of fuses. The investigation shows that the values of the pre-arcing $I^2t$ are higher than those which correspond to the adiabatic conditions even in the case of very high values of the prospective short-circuit current; moreover, the pre-arcing $I^2t$, for a definite value of the short-circuit current, depends on the making angle. The tests carried out on three types of fuses show a good agreement with the results of the simulation.

## 1. Introduction

The knowledge of the fuse operating characteristics in overload and short-circuit conditions is essential when problems of protection of apparatus and coordination of interrupting devices are faced.

The International Standards, concerning low voltage fuses, indicate the operating characteristics to be provided: the time-current characteristics have to be presented for pre-arcing times exceeding 0.1s; in the case of shorter times, the $I^2t$ characteristics have to be specified. With reference to this last requirement, it has been observed that the heating process is non-adiabatic even in the case of heavy currents which cause the melting of the fuse in short times. In order to evaluate the relevant quantities, the pre-arcing phenomenon of a low voltage fuse for high values of short-circuit currents has been analyzed both by a numerical approach and an experimental investigation on different types of fuses. The investigation shows that the pre-arcing $I^2t$ depends on the current value also in the case of short pre-arcing times and, for a defined current value, on the making angle.

## 2. Numerical simulation of the heating process

The phenomenon of non adiabatic heating of the fuse element has been faced by a numerical simulation. Fig.1 shows a scheme of the fuse element under consideration.

The fuse heating is described by the following equation:

$$\varrho_o(1+\alpha\theta)j^2 = -\lambda\frac{\delta^2\theta}{\delta x^2} + c\frac{\delta\theta}{\delta t} \qquad (1)$$

where the first term corresponds to the heat supplied to the fuse element, the second represents the heat lost by conduction and the last the heat stored in the element. The transversal conduction of the heat is not taken into account because the thermal conductivity of the sand is negligible with respect to the copper one. In equation (1) $\varrho_o$ is the resistivity at 0°C of the material of the fuse element, $\alpha$

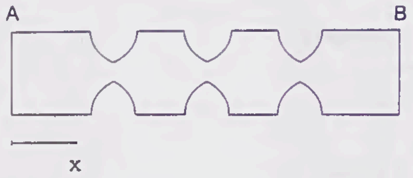

Fig.1 - Schematic representation of the fuse element

is the temperature coefficient of resistivity, $\lambda$ is the thermal conductivity, c is the heat capacity and j is the current density, whose expression is:

$$j(t) = I/S\,[\sin(\omega t+\psi-\varphi) - \sin(\psi-\varphi)\,e^{-t/\tau}] \qquad (2)$$

where $\psi$ is the making angle, $\varphi$ the phase angle of the current, $\tau$ the time constant, I the amplitude of the symmetrical component of the prospective current and S=S(x) the cross section of the fuse element.

In order to solve equation (1), the finite difference method has been used. The computation of the temperature needs the knowledge of the current density in each point of the fuse element. The density, as a consequence of the presence of restricted sections, varies along the length of the element; in order to evaluate it in each subvolume, the current field in the whole fuse element must be computed. To this end, the formal analogy between the electric and the current fields can be advantageously used: in fact, the distribution of the electric field vector is the same for the two fields under consideration, because the electric potential satisfies the Laplace equation in each point of the medium and the same boundary conditions.

On the basis of these considerations the charge simulation method, which is commonly employed to solve the Laplace equation in electrostatic problems, has been used. The method consists in substituting the conducting element with a distribution of discrete charges. Between the surfaces A and B (see Fig.1) a voltage V is applied. In the equivalence with the electrostatic field, these surfaces can be considered as two electrodes of known potential; then the electrodes A and B and the boundary $\Omega$ between the conducting element and the sand are replaced by a discrete charge distribution. The value of these charges is not known, but can be calculated taking into account the boundary conditions:

$$\begin{aligned} V_A &= V \\ V_B &= 0 \\ J_n \Big|_{\Omega} &= 0 \end{aligned} \qquad (3)$$

The application of these conditions to the boundary points leads to a system of n linear equations for the n charges.

This method, that is rather easy to apply and can be used to study field distributions in a complex geometry domain, gives satisfactory results for the aim of this work.

The above method has been applied to study the heating up of different kinds of fuses. The current density distribution has been calculated by the charge equivalent method and the temperature distribution has been obtained by solving numerically equation (1). The knowledge of the temperature distribution along the melting element permits the evaluation of the quantities which characterize the pre-arcing process.

Fig.2 shows the computed temperature distribution in the surrounding area of a restricted section, when the temperature reaches the melting value, for a short-circuit current of 5 kA, cos$\varphi$=0.2 and for two different making angles. The analysis of the two temperature distributions puts in evidence the fact that the process is non adiabatic even at these current values. The phenomenon is more evident for the making angle at which the first loop of current is not sufficient to determine the melting of the element. In this case, at the zero crossing of the current, the energy input reduces and heat is conducted away.

The computed temperature behaviour versus time in the center of the restricted section which first reaches the melting temperature is reported in Fig.3 for two different making angles.

The knowledge of the temperature behaviour in each point of the fuse element

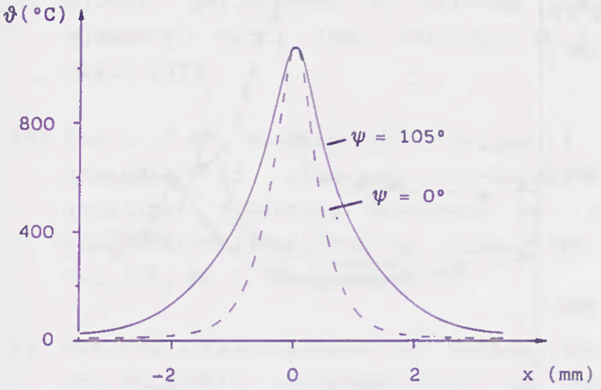

Fig.2 - Computed temperature distribution in the surrounding area of a restricted section, when the melting temperature is reached, for a short-circuit of 5 kA, power factor equal to 0.2 and for two different making angles.

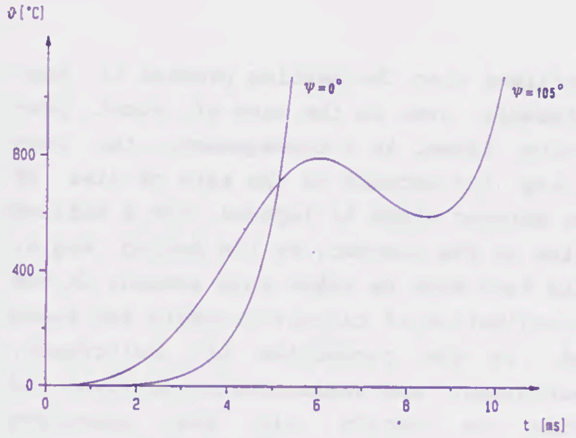

Fig.3 - Computed temperature distribution versus time in the centre of the restricted section which first reaches the melting temperature for a short-circuit current of 5 kA, power factor equal to 0.2; the curves are referred to two different making angles.

permits the evaluation of the let-through energy ($I^2t$) necessary to lead the element up to the melting temperature. Then, the computed behaviours of the melting $I^2t$ versus the making angle have been obtained for different current values. These behaviours are shown in Fig.4 for current values of 5, 10, 25 and 50 kA, power factor equal to 0.2.

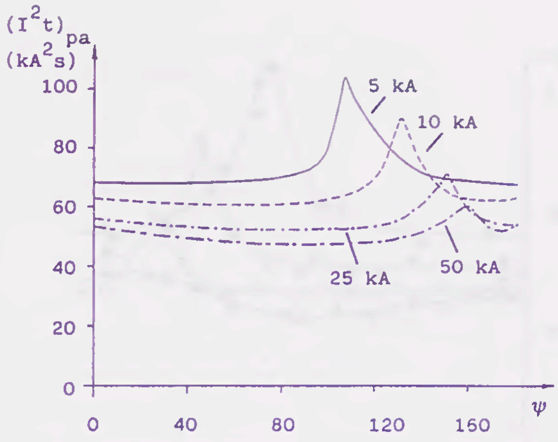

Fig.4 - Computed behaviour of the melting $I^2t$ versus the making angle, for different short-circuit currents, in the case of a 160 A fuse.

## 3. Experimental investigation

In order to verify the validity of the computed results, an experimental investigation has been carried out.

Three different kinds of fuses rated 160, 200 and 250 A, 500 V, 50 Hz, have been tested in an a.c. circuit supplied at 418 V with power factor equal to 0.2 with prospective currents of 5, 10, 25 and 50 kA.

For each value of current the pre-arcing time and $I^2t$ have been recorded for different making angles. The results are illustrated in three diagrams (Fig.5, 6, 7) corresponding to the three types of fuses.

The experimental behaviours of $I^2t$ versus the making angle are similar to the computed ones and the making angle corresponding to the maximum $I^2t$ is correctly simulated by the calculation. The comparison between the measured and the computed results shows that the calculated $I^2t$ values are less than the experimental ones. The difference can be explained taking into account the fact that the computation has been stopped at the instant at which the melting process starts; to reach the value of pre-arcing $I^2t$ the further heating of the fuse until the arc is formed should be considered.

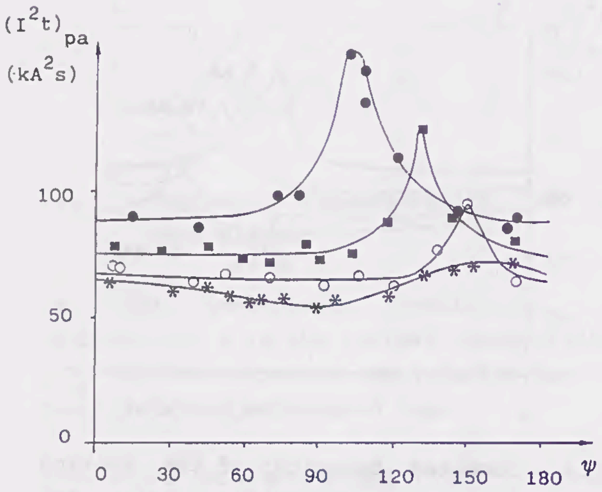

Fig.5 - Experimental behaviour of the pre-arcing $I^2t$ versus the making angle for a 160 A fuse:

- ●) short-circuit current = 5 kA
- ■) short-circuit current = 10 kA
- ○) short-circuit current = 25 kA
- ✱) short-circuit current = 50 kA

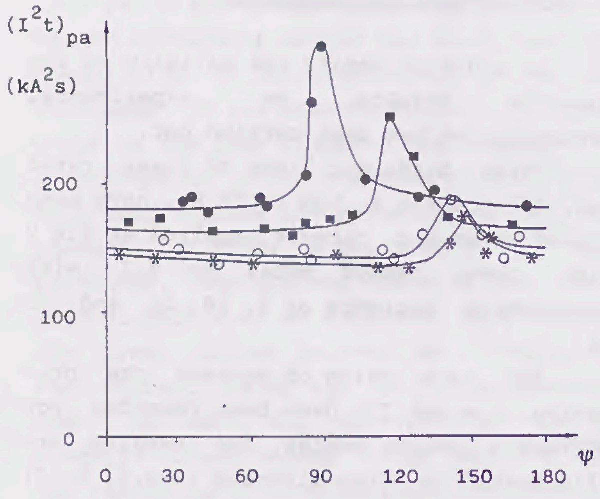

Fig.6 - Experimental behaviour of the pre-arcing $I^2t$ versus the making angle for a 200 A fuse:

- ●) short-circuit current = 5 kA
- ■) short-circuit current = 10 kA
- ○) short-circuit current = 25 kA
- ✱) short-circuit current = 50 kA

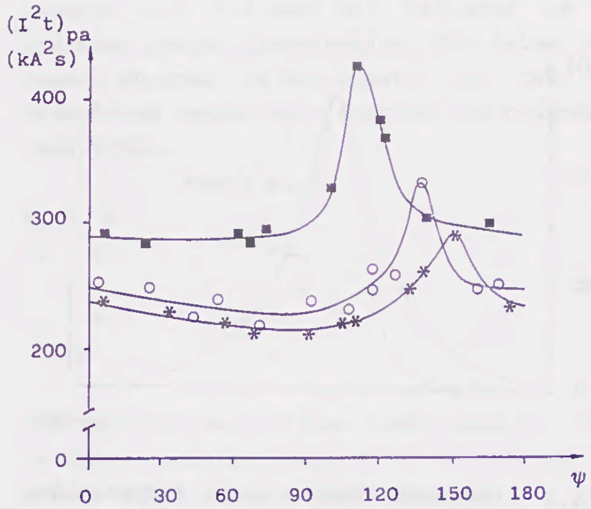

Fig.7 - Experimental behaviour of the pre-arcing $I^2t$ versus the making angle for a 250 A fuse:

- ■) short-circuit current = 10 kA
- ○) short-circuit current = 25 kA
- ✱) short-circuit current = 50 kA

## 4. Conclusion

Both from the numerical analysis of the heating phenomenon and the experimental investigation, carried out with test current up to 50 kA on fuses with notched-strip elements, it has been confirmed that the heating process is non-adiabatic even in the case of short pre-arcing times. As a consequence, the pre-arcing $I^2t$ depends on the rate of rise of the current which is imposed, for a defined value of the current, by the making angle. This fact must be taken into account in the co-ordination of circuit-breakers and fuses and in the protection of switchgear, controlgear and semiconductor devices, in order to verify all the operative conditions which can occur in actual installations.

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