NUMERICAL ANALYSIS OF ELECTRICAL CONTACTS OF CONTROL DEVICES PROTECTED BY FUSES

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1 Introduction

One of the most frequent applications of fuses is the protection of control apparatus against short-circuit. With respect to other short-circuit protective devices, fuses present many advantages due both to economical aspects and to their operating characteristics, such as promptness of intervention, cut-off current and I^2t let-through.

A correct choice of the protective fuse can avoid damages to control apparatus, as contactors and motor starters, and in particular the welding of contacts, which in some cases could lead to serious consequences not only for the protective apparatus, but also for the plant.

In order to obtain an adequate protection of the control device, the thermal and mechanical phenomena that occur in the fuses and in the protected devices has to be accurately known. To this end, a model that permits the simulation of the behaviour in short-circuit conditions of the fuse element, during the pre-arcing and arcing period, and the contemporary evaluation of the heating process of the protected contact elements could result very useful to obtain indications about the possible contact welding.

As regards the fuse model in the pre-arcing period, the current distribution and the heat exchange inside the element must be taken into account, neglecting, for short-circuit current, the heat transferred to the other fuselink parts because of their relatively low thermal conductivity and the shortness of the considered period [1]. In the arcing phase the model must be able to evaluate the arc voltage in order to predict the current behaviour in the protected circuit. Different models have been proposed in literature; between them, the model developed by Gnanalingam and Wilkins [2,3] has been considered and used in this context.

The fuse model is coupled with a contact model which allows the determination of the contact transient heating taking into account the deformation of the material. The output of the fuse model, in the form of current behaviour applied to the contact model, permits the evaluation of the contact thermal behaviour up to the melting point.

2 Numerical models

2.1 Analysis of the problem

The modelling of contacts protected by fuses is complex, because it involves the study of different phenomena. As regards the temperature evolution inside both the devices, the interaction between thermal and electric current fields has to be accurately analyzed; besides, in the case of the contacts the mechanical deformation due to contact pressure and temperature increase in the contact region has to be considered, whereas for the fuses the evolution of the electric arc has to be studied by a suitable model.

The system under study is constituted by a voltage source $u_S(t)=\sqrt{2}\,\sin(\omega t+\psi)$ and a load (having resistance R and inductance L) in series to the fuse element which protects the contacts (**Fig. 1**).

Since the contacts are assumed to remain closed, the current in the circuit is determined only by the load impedance and the voltage across the fuse element. As a consequence, the study of the fuse and the contacts can be faced separately. First the behaviour of the current is determined by analyzing the pre-arcing and the arcing period of the fuse element; then, known the current which flows through the contacts, their temperature increase and the risk of possible welding are analyzed.

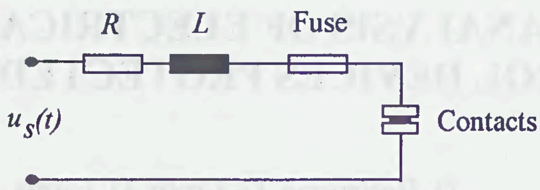

Fig. 1 - Scheme of the circuit with a fuse in series to the contacts

2.2 Fuse model

During the pre-arcing period, the heating of the fuse strip is analyzed by considering the interaction between electric current and thermal field. During this phase, the heat exchange between the strip and the filler is neglected because of the rapidity of the phenomenon.

The problem can be conveniently reduced to a 2D study taking advantage of the symmetry of the elements (the field quantities practically do not vary along the thickness).

The electric current field is governed by the Maxwell equations

$$rotE = 0 \qquad divJ = 0 \qquad J = \frac{1}{\rho} E \tag{1}$$

where E is the electric field, J is the current density and ρ is the electric resistivity, which depends on temperature ϑ. Equation $rotE=0$ allows the introduction of a scalar potential Φ, with

$$E = -grad\,\Phi \tag{2}$$

From (1) and (2) the final current field equation can be written:

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial \Phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial \Phi}{\partial y}\right) = 0 \tag{3}$$

The thermal equation represents the balance between the heat generated, the heat lost by conduction and the heat stored in the element:

$$c\,\frac{\partial \vartheta}{\partial t} = \rho J^2 + \lambda\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2}\right) \tag{4}$$

where c is the heat capacity, λ is the thermal conductivity and J is the current density modulus. The temperature time derivatives is expressed by the Euler approximation

$$\left.\frac{\partial \vartheta}{\partial t}\right|_t = \frac{\vartheta(t) - \vartheta(t - \Delta t)}{\Delta t} \tag{5}$$

where Δt is the time step.

The spatial derivatives in field equations (3) and (4) are approximated by the Finite Difference Method (FDM) leading, together with the boundary conditions, to an algebraic system of equations. The fuse element is then discretized by a non uniform grid, assuming as unknowns the temperature and the scalar potential in each node of the mesh.

The solution of the electric current and thermal field is inserted in a step-by-step time procedure starting from known conditions. At each time step, the distribution of current density and temperature is evaluated inside the element. When the melting temperature is reached in a restricted section, an electric arc appears and its evolution is treated using [2,3]. Following this model, which permits the reproduction of the fuse performances with good accuracy by means of semi-empirical relationships, the arc is supposed to be composed of a given number of *lumen segments*, whose dimensions vary during time following defined differential equations. At each time step the number of *lumen segments* increases and new differential equations are introduced. At the generic instant t_n, being K the number of *lumen segments*, the differential equations are:

$$\frac{di}{dt} = \frac{u_s - Ri - u_f}{L}$$

$$\frac{dx}{dt} = \left[a + b\left(\frac{i}{n_p}\right)^{0.6} \right] \frac{i}{n_p S} \tag{6}$$

$$\frac{dA_j}{dt} = \left[\alpha_o + (\alpha_m - \alpha_o)\left(1 - e^{-t_j/\tau}\right) \right] \frac{E_j}{\rho_f \left(C_f \Delta T + L_f\right)} \frac{i}{n_p} \qquad j = 1, \ldots, K$$

where i is the current, u_s is the supply voltage, u_f is the arc voltage, x is the arc length, n_p is the number of strips in parallel, S is the cross sectional area of the fuse and A_j, E_j and t_j are respectively the area, the axial arc gradient and the time measured from the beginning of the j-th *lumen segment*. The other quantities are parameters which depends on the filler and the strip material, determined by experimental studies.

2.3 Contact model

The modelling of the contact elements involves the study of the interaction between electric current field and thermal field [4,5], taking into account the mechanical deformation of the elements. The model is developed under the assumption of cylindrical symmetry of the contact elements (coordinate system (r, ϕ, z)).

The electric current field is governed by equations (1); in this type of problem, it is convenient to introduce a vector potential T, considering that $divJ=0$:

$$J = rotT \tag{7}$$

Taking into account the problem symmetry, the vector potential T has only the component T_ϕ which depends on the coordinates r and z:

$$T = \left(0, T_\phi(r, z), 0\right) \tag{8}$$

The resulting current field equation can then be derived:

$$\rho\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \frac{\partial \rho}{\partial r}\left(\frac{\partial T}{\partial r} + \frac{T}{r}\right) - \rho\frac{T}{r^2} + \frac{\partial \rho}{\partial z}\frac{\partial T}{\partial z} + \rho\frac{\partial^2 T}{\partial z^2} = 0 \tag{9}$$

where the unknown T is the component T_ϕ.

Similarly to the fuse model, the thermal field is described by the equation:

$$c\frac{\partial \vartheta}{\partial t} = \rho J^2 + \lambda\left(\frac{\partial^2 \vartheta}{\partial r^2} + \frac{1}{r}\frac{\partial \vartheta}{\partial r} + \frac{\partial^2 \vartheta}{\partial z^2}\right) \tag{10}$$

If during the transient the contact area reaches a temperature higher than the softening one, it is necessary to take into consideration the deformation; this can be obtained by evaluating the true contact pressure (given by the applied mechanical load minus the contact repulsion force) and the enlargement of the contact area by means of the stress-strain diagrams. The approach is described in detail in [6].

Also for the contact model, a step-by-step time procedure is adopted and the FDM is used to solve the field equations. At each time step, the temperature distribution is evaluated and the deformation of the contact is determined. Known the new contact shape, a new mesh is generated and the current and thermal fields at the following time step are computed.

3. Experimental validation of the model

The experimental validation of the model presents two different aspects: the first one regards the computation of the current behaviour limited by the fuse operation, while the other is the evaluation of the accuracy of the temperature evolution computed inside the contact element.

As regards the first problem, the comparison between numerical results and experiments has been performed on the current behaviour in order to verify the capability of the model to reproduce the limiting effect of the fuse. To this end, different fuses have been considered and the limiting current behaviours, obtained under different circuit configurations, have been compared.

Similarly, extensive tests have been performed on the contact model [7]; the verifications were carried out by imposing to the contact elements the experimental current behaviour. Since the temperature evolution of the contact surface during the transient cannot be directly measured, the comparison was carried out on the evolution of the contact voltage drop and on the initial and final contact area (measured by microscope).

As an example, two different tests are reported in the following. The first one refers to a fuse of rated current of 50 A (type gI) and contact elements of contactors (contact element radius of about 3 mm); the mechanical load on the contacts was 14 N. **Fig. 2** reports the computed and experimental behaviours of the limited current obtained with a prospective current of 2.7 kA. The comparison between numerical and experimental contact voltage drop is shown in **Fig. 3**. Because of the range of variation of the experimental contact voltage, the maximum and minimum voltage drop versus time, obtained from a group of seven tests carried out under the same conditions, are reported.

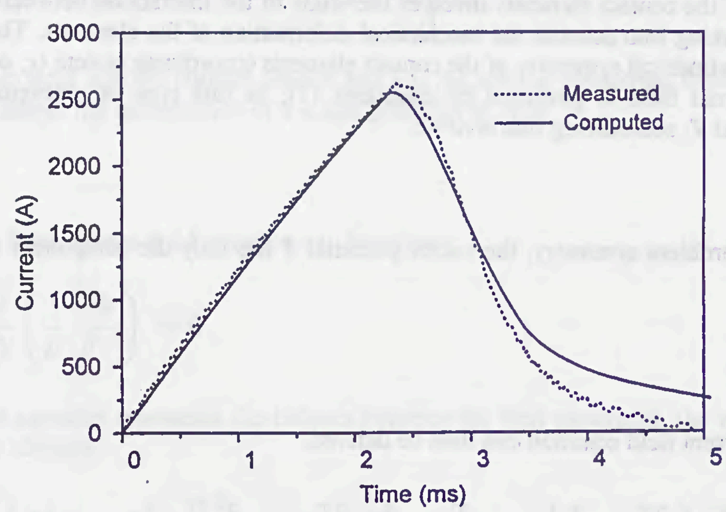

Fig. 2 - Computed and measured limited current (fuse 50 A - gI)

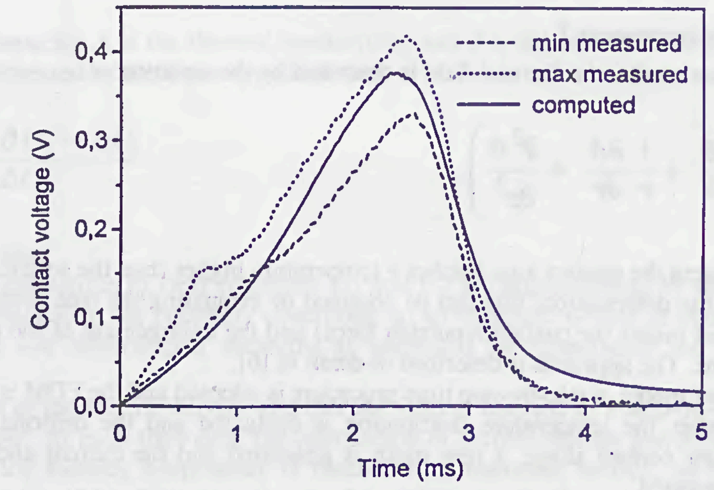

Fig. 3 - Computed and measured contact voltage corresponding to Fig. 2

The second test refers to a 50 A fuse (type aM) and the same contact elements but with a mechanical load of 20 N; the circuit conditions are the same of the previous test. **Fig. 4** shows the comparison between the numerical and the experimental current behaviour, while the contact voltage drops are compared in **Fig. 5**.

The experimental validation of the results has evidenced that the models reproduce with satisfactory accuracy the behaviour of the system fuse-contact. Both the models give good results as concerns the reproduction of the phenomena during the increase of the current (pre-arcing period of the fuse); on the contrary, some discrepancies with experiments are present during the descending part of the current behaviour (arc phase in the fuse). Anyway, the aim of the model is to evaluate the maximum temperature reached by the contact surface, which is obtained during the raising part of the current.

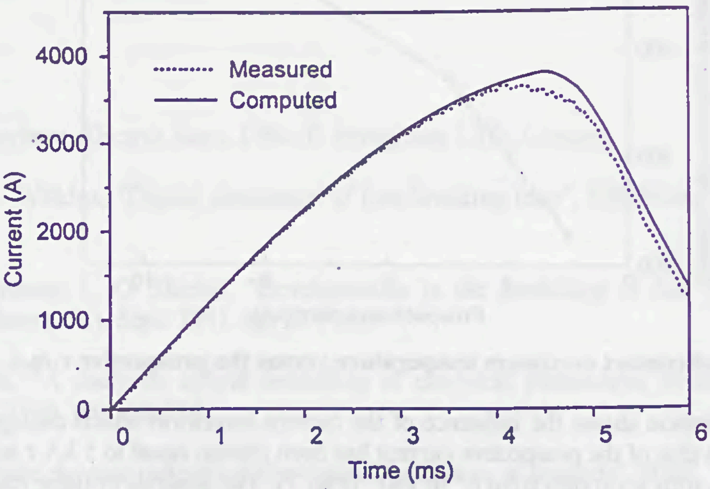

Fig. 4 - Computed and measured limited current (fuse 50 A aM)

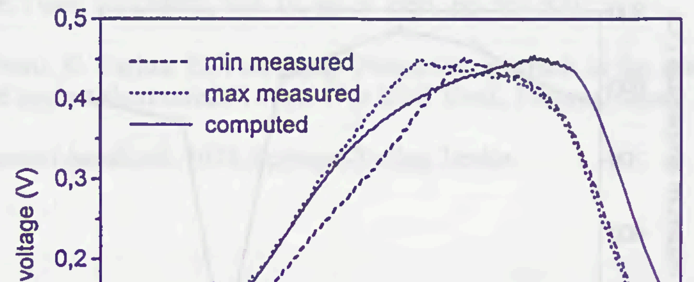

Fig. 5 - Computed and measured contact voltage corresponding to Fig. 4

4. Application of the model

The fuse-contact model has been applied to the analysis of different operating conditions, with the aim of determining their influence on the maximum temperature reached by the contact area. In such a way it is possible to have preliminary indications about the limit conditions which can lead to the welding of the contacts, if the opening of the contact does not occur.

The analysis has been developed considering a 50 A fuse (type gI) which protects the contact elements considered in the previous verifications. For each operating conditions the fuse model has been used to determine the current behaviour and successively the maximum temperature reached by the contact has been computed by the contact model.

First, the influence of the prospective current flowing in the circuit has been analyzed. Current values ranging from 3 kA up to 10 kA (r.m.s. value) have been considered; the power factor of the circuit is fixed to 0.3

and the making angle ψ has been chosen in order to obtain a symmetrical waveform; finally, the mechanical contact load has been imposed to 20 N. The maximum temperatures reached by the contact area during the transient are plotted in **Fig. 6** versus the prospective current. As can be noted, this fuse limits the maximum temperature reached by the contact surface to values lower than the melting point for prospective currents up to 10 kA.

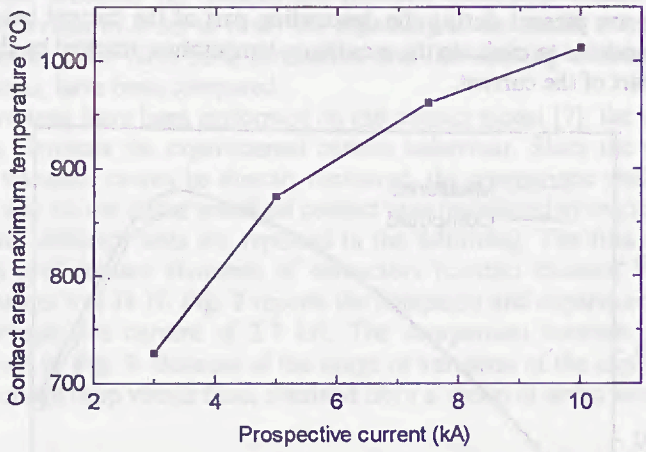

Fig. 6 - Computed contact maximum temperature versus the prospective r.m.s. current value

The second application shows the influence of the current waveform which changes modifying the value of the making angle. The value of the prospective current has been chosen equal to 5 kA r.m.s. (power factor of 0.3 and contact force of 20 N) with ψ varying from 0° to 180° (**Fig. 7**). The analysis of these results shows that, in this case, the maximum thermal stress is obtained in the case of symmetrical shape of the prospective current (ψ of about 70°).

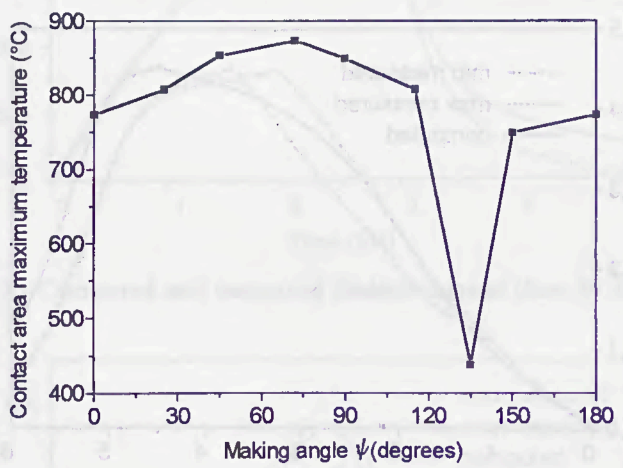

Fig. 7 - Computed contact maximum temperature versus making angle

Finally, it is worth analyzing the influence of the fuse characteristics which modify the behaviour of the limited current. Four different types of fuses have been considered: 20 A (type A), 35 A gI (type B), 50 A gI (type C) and 50 A aM (type D). The prospective current is fixed to 5 kA (power factor 0.3, contact force 20 N):

Table I - Influence of the fuse on the contact maximum temperature

Fuse type	Cut-off current (A)	Contact maximum temperature (°C)
A	2500	570
B	3290	876
C	3260	874
D	5580	1083 (*)

Note: (*) The melting point is reached

5. Conclusions

The tests carried out and the numerical simulation of the heating of contact elements protected against short-circuit by fuses indicate that the model is able to reproduce with satisfactory accuracy the thermal behaviour of contacts with particular reference to the maximum temperature reached by the contact surface during the heating transient. As a consequence, it could be used to obtain preliminary indications about the possible risk of contact welding, in the case of closed contacts. Future development of the model will be the study of the contact thermal behaviour in case of higher values of current, leading to the opening of the contacts with the presence of short arcs.

6. References

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