FUSE-ELEMENT - AGEING AND MODELING

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Abstract :

As motor fault current protection the "gI" or "aM" fuses come sometime to prematurely melting, not in accordance with standards.

A better knowledge of the ageing mechanisms should permit to design new types of fuse element.
The cycle loading investigations on a 100A gI fuse (size 1 of IEC 269 Standard) were performed on a high power testing station.
Metallographie observations were made as a function of the fuse element ageing. The solder migration around the copper dissolutions explain the phenomena.
Then, to redure the ageing two possibilities appear :

- to prevent the solder migration
- to delay the dissolution time

All these possibilities require to know the temperature along the fuse element, therefore the heat transfers were modeled.

The temperature evolutions were calculated in the fuse element and in the sand.

The model validity was checked by comparing the calculated and experimental fuse time/current fonction.

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It often occurs that in the production units the fuses melt prematurely after several overloadings which, in accordance with the standards did not and should not lead to melting.
In order to study the fuses ageing, we have submitted them to overload cycles, and we first measured the variation of the electric withstand, according to the number of cycles. Then, we performed some metallographic observations at various stages of ageing. At least, we carried out the modeling of thermal transfers in order to know the distribution of temperatures within the fuse.

1. EXPERIMENTAL STUDY

The studied fuse is represented on figure 1. Its main characteristics are :

- fuse HPC according to standard IEC 269 gI 100A
- fuse element of copper + tin
- application voltage : 500V AC

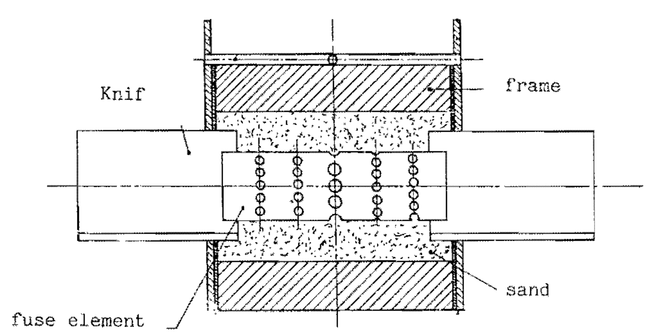

Figure 1

The fuses have been first submitted to repeated ageing cycles made of a load of $3xI$ = 300A during 1,82 s followed by a period of rest of 12 s. The time of 1,82 s corresponds to 0,9 times the average melting time for 12 fuses submitted to a load of 300 A. These cycles have been performed to a serie of fuses and the melting process occured for an average number of cycles N = 1614.

Then the resistance of 22 fuses submitted to these same cycles have been measured for $\frac{N}{2}$, $\frac{3N}{4}$, $\frac{7N}{8}$, cycles

First, we can notice that all fuses do not age in the same way, some melted prematurely. We nevertheless can note that according to the ageing, the resistance increases, then decreases and increases again before the melting process.
A metallographic study has been carried out in order to explain this behaviour.
For fuses with little developed ageing, the tin has melted, is oxydised and presents marks of sand grains and has barely migrated. On the surface, the copper is oxidised, especially in the areas between the holes. On the metallographics (figure 2) we can see that the copper presents the same volume as the copper of a new fuse. There are some toothlike imperfections in tin.
For fuses with more developed ageing, the tin is oxidised, it migrated and went to the other side through the central holes. Besides them, we can see toothlike imperfections near the copper (figure 3) together with a slight reduction of the fuse section. The remaining copper has not been modified.
For fuses with extremely developed ageing, the tin has completely limited the copper parts between the holes and it is oxidised. On the metallographics we can see that the copper is completely dissolved in the areas between the holes and has been replaced by tin with a great amount of toothlike imperfection (figure 4). These toothlike imperfection corresponds to the dilution of copper within tin. Regarding the volume, the remaining copper has not been modified.

The ageing is originated by the tin migration at the copper surface towards the areas between the holes and by the diffusion of tin within copper there seams not to be a grain sweling.
In a first step, the oxydation increases the withstand, then when the tin migrates into the inter-holes area, the copper is partly short-circuited, which decreases the resistance, then the copper dissolves which increases the resistance until the melting process.

Other tests have been carried out, at low constant overload (1,6xIn) for increasing durations and at high overload (10xIn) during 0,08 s followed by rests of 600 s, these cycles have been repeated until melting of one fuse of the range.
For these tests, the ageing processes occur the same way as those previously described.
In order to limit the ageing, it is possible :

- to treat the copper surface which makes it less wetable and which bothers the tin migration.
- to place a deposit at the copper surface wich acts as a diffusion barrier and which makes the copper dissolves slowlier.

These various possibilities require to know the distribution of the temperatures and therefore, we carried out a modeling of heat transfers in the fuse and sand which surrounds it.

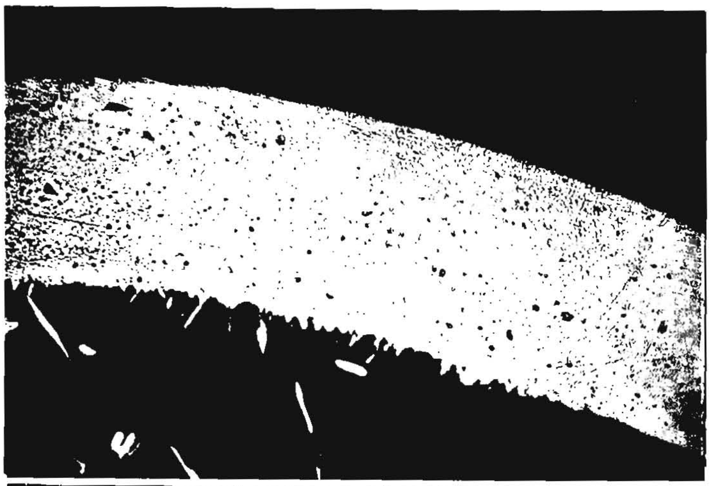

Figure 2

metallographic little ageing copper-tin

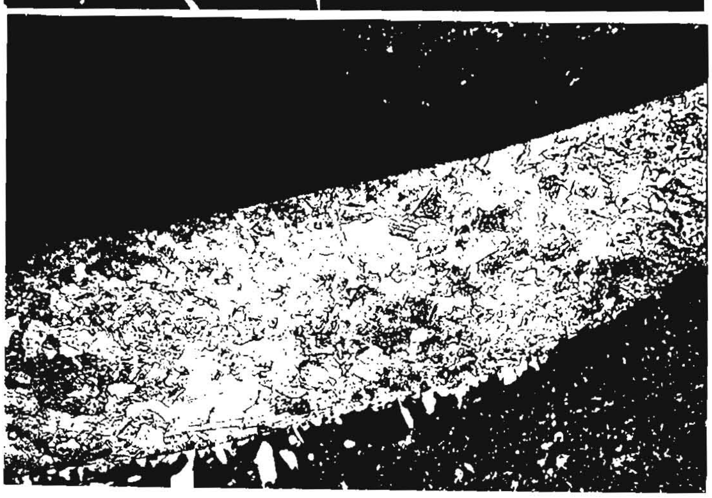

Figure 3

metallographic more developed ageing copper-tin

Figure 4

metallographic extremely developed ageing copper dissolved in tin

2. MODELING OF THE HEAT TRANSFERS

The power by length unit of the fuse is represented on figure 5. (For symmetrical reasons, the calculation has been made on a quarter of the fuse).
Each part of the curve P (Y) has the following shape : $P(y) = I^2 \left(A_{0+3i}\, y^2 + A_{1+3i}\, y + A_{2+3i} \right) \quad i = 0,1,2,3,4,5$

The parts at the holes levels are parabolic so that the maximum correspond to the powers extracted at the abscissa of the holes centers and so that the surfaces under the parabola are equal to the powers extracted at the holes level. The uniform parts represent the heat emission between the holes.

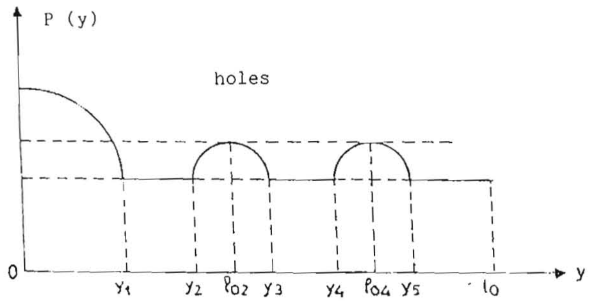

Figure 5 Power dissipated along the fuse element

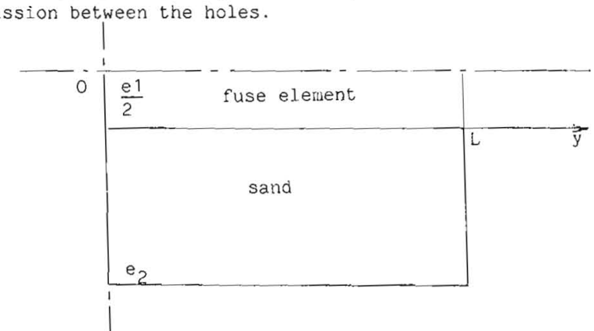

Figure 6

For a current I passing through the fuse during a time DT, the temperature range can be obtained from the following pattern (see figure 6)

$$\frac{\partial^2 T_1}{\partial y^2} = \frac{1}{\alpha_1} \frac{\partial T_1}{\partial t} \qquad \frac{\partial T_1}{\partial y} = 0 \text{ for } y = 0 \qquad k_1 \frac{\partial T_1}{\partial u} = - h_1 T_1 \text{ for } y = L$$

$$T = \frac{dt}{e_1 \ell \rho_1 c_1} \left[I^2 \left(A_{0+3i}\, y^2 + A_{1+3i}\, y + A_{2+3i} \right) - \varphi \right] \text{ at } t = 0$$

The term in square brackets represents the heat emission by joule effect in the fuse and φ the thermal leaks towards the sand.
For the sand :

$$\frac{\partial^2 T_2}{\partial x^2} = \frac{1}{\alpha_2} \frac{\partial T_2}{\partial T} \qquad \frac{\partial T_2}{\partial x} = 0 \text{ at } x = 0 \qquad k_2 \frac{\partial T}{\partial x} - h_2 T \text{ for } x = e_2$$

$$T = \frac{dt}{E \ell \rho_2 c_2} \varphi \text{ for } t = 0 \qquad 0 < x < E$$

The solution of this pattern is (1) :

$$T_1 = \frac{dt}{e_1 \ell \rho_1 c_1} \left[\Sigma_n \frac{1}{N_{1n}} \left(I^2 \left(\Sigma_{j=0}^{17} A_j F_{nj} \right) - \varphi F_n \right) \cdot \cos\left(\gamma_{1n}\, y \right) \exp\left(- \alpha_1 \gamma_{1n}^2 t \right) \right]$$

$$N_{1n} = \frac{1}{2} \left[L + \frac{h_1 \lambda_1}{(\gamma_{1n} \lambda_1)^2 + h_1^2} \right]$$

(Each therm marked by J corresponds to a term A)

$$F_{nj} = \int_{y_i}^{y_{i+1}} \left(A_{0+3i}\, y^2 + A_{1+3i}\, y + A_{2+3i} \right) \cos\left(\gamma_{1n}\, y \right) dy$$

$$F_n = \int_0^L \varphi \cos\left(\gamma_{1n}\, y \right) dy \; ; \quad \gamma_{1n} \text{ solution of } \cot g\, \gamma_{1n} L = \gamma_{1n} \lambda / h_1$$

$$T_2 = \frac{\varphi\, dt}{\ell \rho_2 c_2} \Sigma_m \frac{1}{N_{2m}} \cos \varphi \left(\gamma_{2m} \cdot x \right) \exp\left(- \alpha_2 \gamma_{2m}^2 t \right) \; ; \quad N_{2n} = \frac{1}{2} \left[e_2 + \frac{h_2 \lambda_2}{(\gamma_{2m} \lambda_2)^2 + h_2^2} \right]$$

γ_{2n} solution of $\cot g\, \gamma_{2n} e_2 = \gamma_{2m} \lambda_2 / h_2$

This auxiliary result permits one to calculate the temperature range for a current I according to factor time.

We are describing here the method for a constant current I from t = 0. by applying DUHAMEL theroem (2), the solution is :

$$T_1 = \int_0^t \frac{1}{e_1 \ell \rho c_1} \left[\Sigma_n \frac{1}{N_{1n}} \left[I^2 \left(\sum_{j=0}^{17} A_j F_{nj} \right) - \varphi(t) F_n \right] . \cos\left(\gamma_{1n} y\right) \exp\left(- \alpha_1 \gamma_{1n}^2 \left(t - Z\right)\right)\right] dZ$$

$$T_2 = \int_0^t \frac{\varphi(t)}{\ell \rho_2 c_2} \; \Sigma_m \frac{1}{N_{2m}} \left[\cos\left(\gamma_{2m} x\right) \exp\left(- \alpha_2 \gamma_{2m}^2 \left(t - Z\right)\right) dZ\right.$$

By taking the LAPLACE transformation of these expressions :

$$\overline{T_1} = \Sigma_n \frac{\cos \gamma_{1n} y}{e_1 \ell \rho_1 c_1 N_{1n} \quad P + \alpha_1 \gamma_{1n}^2} \left[I^2 \left(\Sigma_{j=0}^{17} A_j F_{nj} \right) \frac{1}{P} - \overline{\varphi}_{(P)} F_n \right]$$

$$\overline{T_2} = \Sigma_m \frac{\cos(\gamma_{2m} x)}{\ell \rho_2 c_2 N_{2m}} \left[\frac{\overline{\varphi}(P)}{P + \alpha_2 \gamma_{2m}^2} \right]$$

$\overline{\varphi}_P$ is determined by using a coupling condition between the middles 1 and 2 : $\frac{1}{L} \int_0^L \overline{T_1} \, dy = \left(\overline{T_2}\right)_{x=0}$

which shows that the average temperature of the middle 1 is equal to the temperature in x = 0 of the middle 2.

The expression of φ (P) is transfered to $\overline{T1}$ and $\overline{T2}$
The temperature of the middles 1 and 2 is calculated by using a numerical method of LAPLACE inversed transformation (3).

NOMENCLATURE :

1. - Indication for the fuse element
2. - Indication for the sand
-. - LAPLACE transformation
T. - Temperature
t. - Time
y and x - Coordinates
L. - Length of the fuse
l. - Width of the fuse
e. - Depth
K. - Conductivity
ρ - Volumic mass
c. - Massic heat
h. - Exchange coefficient with the outer environment
α - Diffusivity
I. - Intensity
φ - Flow exchanged between the fuse element and the sand
P. - Variable in LAPLACE transformation
ε - Infinitely little

The validity of the hypothesis accepted in this pattern have been checked out by comparing the curves of experimental meltings and the melting curves calculated for various fuses (exemple figure 7).

For this very fuse, the temperature evolution arround the hole is shown on figure 8 as regards to the nominal intensity. We can see that in these conditions, the tin has melted.

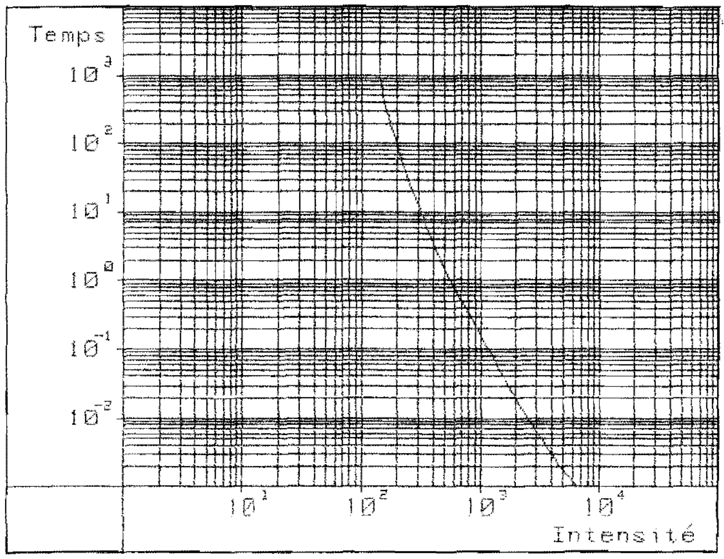

Figure 7

Calculated melting curve
(time-current)

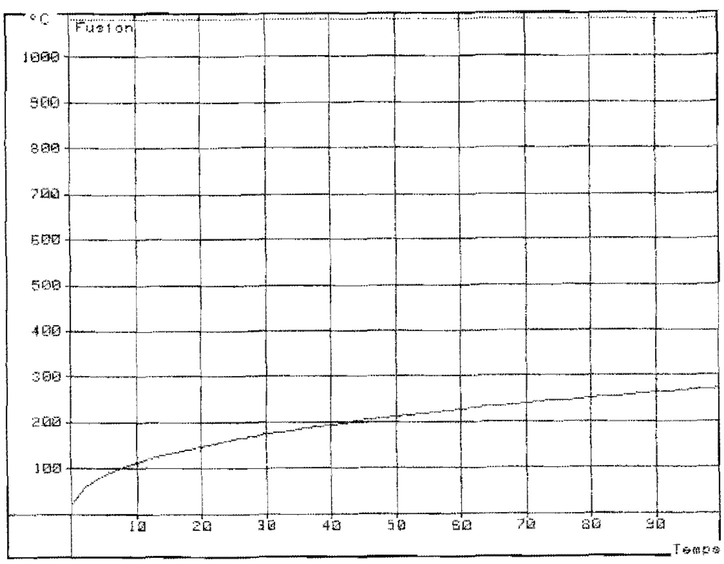

Figure 8

Temperature evolution at one aera of fuse element

CONCLUSION :

Modeling of the heat transfer has been performed on a HP calculator with graphic printing. It enables to totally simulate the fuse operating in prearc period.

Although this pattern is suited to a given technology of fuse blade, it can easily be modified according to other conceptions.
Finally, the experimental checking of the curves time/current confirmed the validity of the pattern together with its significance regarding the optimation of the fuse element, either according to the relevant standard or according to economical matters.

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(2) N.ÖZISIK " " J.Wiley and Sons page 246 to 265

(3) B.LASSAGNE These Nantes 11-1985

Session III

ARCING AND DISRUPTION PHENOMENA 1

Chairman: Dr. L. Vermij