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CUMULATIVE-AGEING APPROACH FOR DETERMINATION OF THE LIFE-DURATION OF FUSES IN CASE OF MULTI-LEVELS CYCLES

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Cumulative-ageing approach for determination of the life-duration of fuses in case of multi-levels cycles

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Abstract

Fuses-manufacturers carry out many tests in order to evaluate the life-duration of their products, but tests cannot match exactly actual conditions in the field. Then, they have to extrapolate test-results for estimating life-duration in operation. MERSEN drew out a method based on determination of coefficients applied to the fuse-rating for withstanding the required life-duration.

But, fuses are often submitted to complex conducting-cycles, combining short and long periods, with more or less high current-values, even with off-times. The common and simple approach is to calculate coefficients corresponding to each stress and to combine them by multiplication.

This can lead to excessive restriction of the current in the fuse, or reversely to large fuse-ratings, increasing I^2t and reducing the short-circuit-protection. In this paper, MERSEN will propose an improved method using accumulative-effect approach. This method will help the application-engineers to better choose the fuse and improve the quality of the equipments.

Keywords: electric fuse.

1. Fatigue ageing of ultra-fast fuses

Protection of power-semiconductors needs to develop specific ultra-fast fuses, according to IEC standard 60269-4. Indeed a very fast operation of the fuses is required in order to save semi-conductors in case of short circuits in the field. In other words, for a given rated-current, fuses will have to present a minimal conducting area ; or, on another hand, for a given I^2t, they will be able to carry a maximal current.

Unfortunately, carrying a large current doesn’t go without any risks. The biggest of them is the occurrence of some metallurgical fatigue phenomenon. Let us introduce briefly what happens. Due to Joule-effect, the current-conduction induces a heating of the conductors, specially at the notches of fuse-elements. Then, the temperature would causes some dilatation of the metal. But, as this dilatation is interfered with sand around the notches, stresses are developed. Note that stresses are generated all along the element, but they are amplified on the restrictions of the necks.

When fuses are used in a cyclic way, the alternation of stressed and relaxed states leads to ageing by fatigue phenomenon. This phenomenon is well known by metallurgist-engineers. For instance in bridges-building, in automotive-engines, in aerospace-industry, people take big care of it. Nevertheless, in case of power-semi-conductor-fuses, the problem becomes more difficult because the metal mechanical properties actually change during the cycle, due to change of temperature. In a previous paper presented at ICEFA-2003[1], we showed that ageing was probably due to a combination of fatigue and creep. As a matter of fact, it is still difficult to calculate by analytical or numerical methods what will be the ageing of fuses.

Another question is the large discrepancy going together with fatigue.

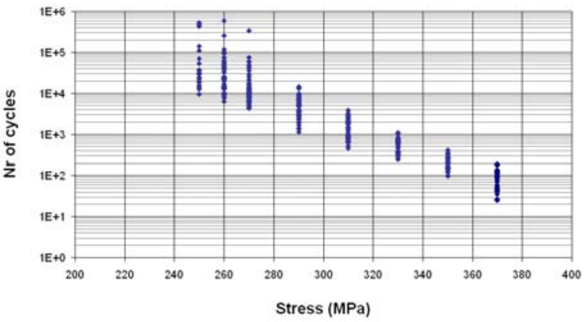

Fig. 1: Rotative-bending fatigue-tests on XC10-steel[2]

Under a characteristic value of the stress, the material will not be subjected to fatigue. But beyond this value, fatigue will occur. As soon as 1870, Wöhler studied fatigue of railways-axles and proposed his law, which is available when fatigue happens, but doesn't take into account any transition to the area where material sustains infinite number of cycles :

$$\log(N) = a - bS \qquad (1)$$

Fig. 1 shows that in words of numbers of cycles N, the discrepancy runs from 1 to more than 10 at a level of stress S. For example, for S = 290 MPa, N ranges from 1150 to 14500.

mean value is mean(N) = 5208 cycles (2a)
standard deviation is σ(N) = 3550 cycles (2b)

and ratio $$\frac{\sigma(\mathrm{N})}{\mathrm{mean}(\mathrm{N})} = 0.68 \qquad (2c)$$

This is a traumatic and inexact reading of Wöhler's law. It will be more precise to consider that log(N) runs from 3.061 to 4.161.

mean value would be mean(logN) = 3.620 (3a)
standard deviation would be σ(logN) = 0.298 (3b)

and ratio $$\frac{\sigma(\log N)}{mean(\log N)} = 0.082 \qquad (3c)$$

This way of considering the Wöhler's law doesn't only make sense from a mathematical point of view. Also from the physical point of view, it is legible. Indeed, it is now a common knowledge that the fracture-mechanism of fatigue is based on the opening of a crack due to application of cyclic stresses. The increment of the crack is called the C.O.D. (Crack Opening Displacement). And what is interesting is that C.O.D. doesn't occur at each cycle, but corresponds to a block of several cycles.

2. MERSEN's methodology for fuse-determination

For a long time, MERSEN's engineers are aware of this phenomenon and thanks to many tests, could develop a method allowing to correctly choose a fuse. Nowadays requirements from customers concern figures for very long life-durations, up to thirty years, and statistical considerations giving evaluation of tolerances around mean values.

Because of the complexity of calculations based on theory of fatigue, MERSEN's engineers have given priority to statistical analyzes of numerous testsresults. Basically, from their observations, engineers have been brought to consider two tendencies[3].

The first of these tendencies involves cases where it is possible to consider that heating concerns the whole fuse. The current-conduction period is long enough to reach a quasi stabilized field of temperature within the fuse. It is what occurs when the equipment is running during the day and stopped during the night. The stabilized temperature comes when the conduction period is less than about three times the thermal time-constant of the fuse. For most of fuses, stabilisation is got after one hour. Then tests one hour on / one hour off are characteristic of this first approach. The RMS-value of the current is the decisive parameter.

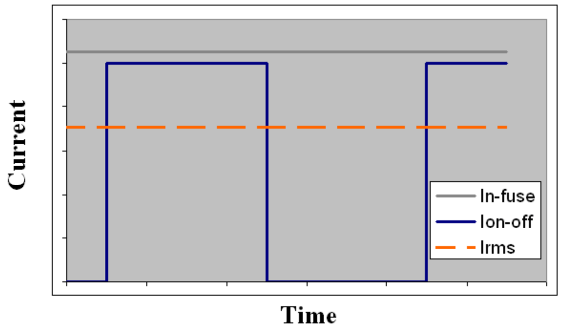

Fig.2: Example of a global heating of the whole fuse. RMS-current is to be taken into account.

MERSEN has introduced a coefficient A as the ratio:

$$A = \frac{I_{RMS}}{In} \,, \qquad (4)$$

where I_{RMS} is the RMS-current of the cycle and In is the rated current of the fuse. MERSEN also defined A2 as the value of A for a life-duration of 30 years. Generally, for ultra-fast fuses, A2 is about 0.60.

A second tendency concerns cases where thermal stabilisation is not achieved, but where peaks of current may induce local heatings of the fuse-elements.

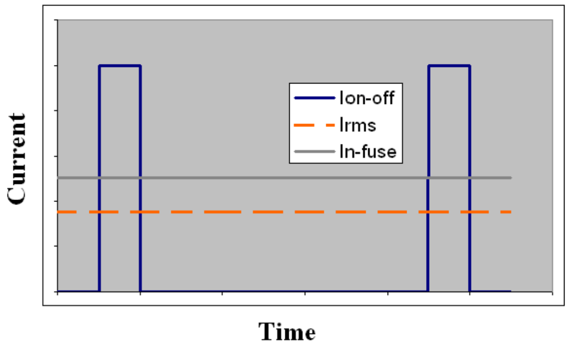

Fig.3: Example of a peak of current. How much is this peak close to the melting point?

Of course, melting temperature is not reached, but as more the local temperature becomes closer to the melting temperature, as more ageing is important.

The decisive issue will be how much the current I_{ON} during the conduction-period t_{ON} will be close to the current I_{melt} which will lead to melting for a conduction-time equal to t_{ON}.

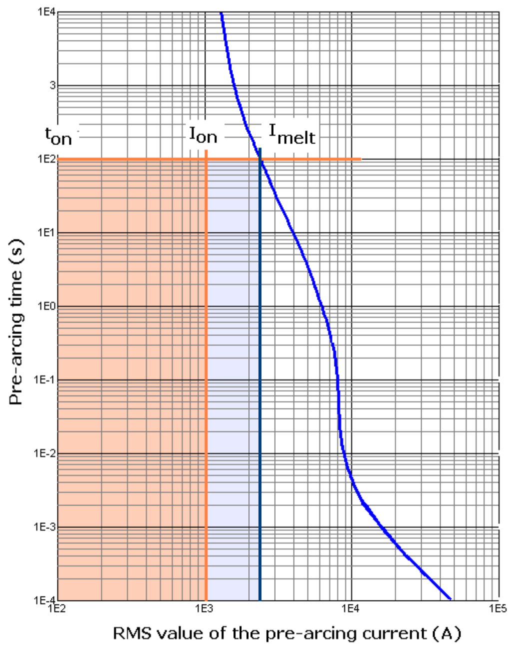

Fig.4: Prearcing-curve with t_{on}, I_{on} and I_{melt}.

MERSEN introduced a coefficient B as the ratio:

$$B = \frac{I_{ON}}{I_{melt}} \,. \qquad (5)$$

As for A2, MERSEN also defined B2 as the value of B for a life-duration of 30 years. Generally, for ultra-fast fuses, B2 is about 0.60.

3. Complexity of the cycling-conditions

Pure rectangular cycles as shown on fig. 2 and 3 are very simple and also very rare. In addition, rated current In and the melting curve are defined under standard conditions that are not of common use.

Several practical parameters will interfere on the life-duration :

- A1 is to be used when the temperature inside the cubicle is above 30°C. This coefficient is calculated from the published coefficient a.
- C1 takes into account the size of the conductors connected to the fuse and the cooling of the terminals
- B_v takes into account the velocity of the air on the fuse. It is calculated from the published B1.
- C_{PE} is to be used when the current-frequency is higher than 100 Hz, because of proximity effect.
- and k is to be applied to A2 for calculating :

  A'2 = k.A2 (6)

  when conduction time and/or stop-time are shorter than one hour.

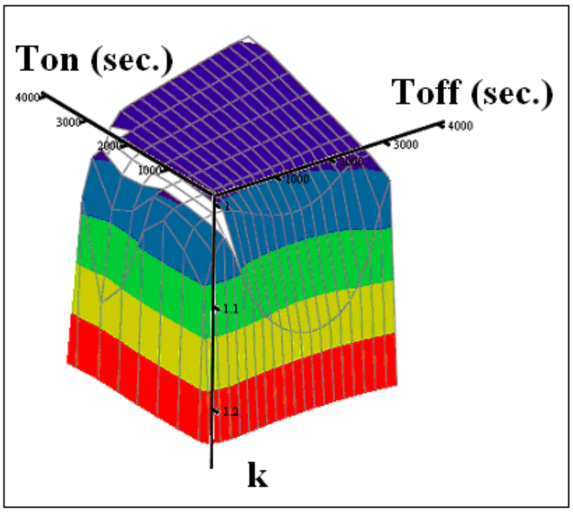

Fig. 5: Coefficient k to be applied to A2 vs t_{ON} and t_{OFF}.

Coefficient k supposes that the cycle presents a simple shape, with a conduction time t_{ON} at I_{ON} and stop-time t_{OFF}. Times t_{ON} and t_{OFF} as well as the value of the current I_{ON} may have different values.

4. Cumulative effects

Moreover than A2 and B2 coefficients which have been defined and determined in order to guarantee a life-duration of 30 years, MERSEN's engineers are able to draw out the ageing-law of the fuse: log(Nr)= f(⍰), where Nr is the number of cycles that the fuse will withstand before opening and ⍰ is the stress it will have to support. The stress ⍰ could be expressed according to different ways :

- current I_{ON} during t_{ON},
- Rms-current I_{RMS} of the cycle during t_{ON} + t_{OFF},
- ration of the current I_{ON} to the rated current of the fuse : $\frac{I_{ON}}{In}$
- ratio A of the current I_{RMS} to the rated current I_n of the fuse : $A = \frac{I_{RMS}}{In}$
- ratio B of the current I_{ON} to the melting-current I_{melt} of the fuse : $B = \frac{I_{ON}}{I_{melt}}$

In the following developments of this paper, let us consider ⍰ as A.

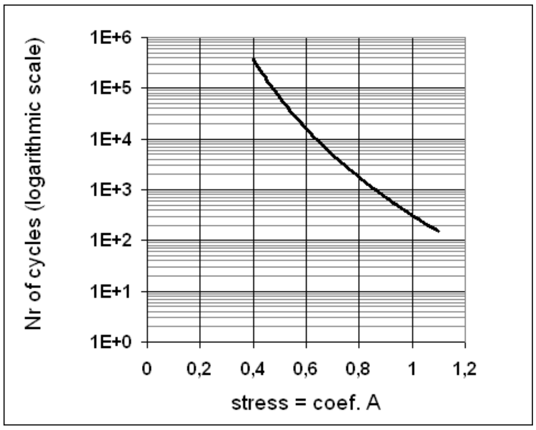

Fig. 6: typical ageing curve (available only for demonstration)

Miner[4] defined *damage* as the ratio at the time t, of the duration spent since time t_0 = 0 to the total expected duration :

$$\text{Damage}(t) = \frac{N(t)}{Nr} \quad (7a)$$

damage also depends on the load :

$$\text{Damage}(t, A) = \frac{N(t, A)}{Nr(A)} \quad (7b)$$

This definition of damage is equivalent to the ratio of total life. In fact more physical observations could be used for describing damage. For instance, a sample submitted to stresses will develop a crack; the depth of the crack can be used as a measure of damage. Another example is with ageing of fuses ; the value of the electrical resistance could be used as a measure of damage. In these two examples, damage is not linear with the ratio of total life.

Here-after, we shall consider damage as linear with the ratio of total life. This will help us for taking into account cumulative effect of several kinds of loads.

Let us suppose that the sample has to be stressed by two kinds of cyclic loads expressed as $A_{(1)}$ and $A_{(2)}$. How does each of them contribute to make damage on the sample and what will be their cumulative effects ?

$$\begin{aligned}&\mathrm{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= f\left[\mathrm{Damage}(t, A_{(1)}), \mathrm{Damage}(t, A_{(2)})\right]\end{aligned} \tag{8}$$

Then, the question will be: what is the function **f**? Answer will be: it depends. And let us take an example.

Example :

The fuse is submitted to cyclic currents. Two kinds of cycles can occur :

- $t_{ON(1)}$ = 1 hour under current I_{ON} followed by $t_{OFF(1)}$ = 1 hour
- series of $t_{ON(2)}$ = 5 minutes under current I_{ON} followed by $t_{OFF(2)}$ = 5 minutes ; each series will count 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$

In addition, long cycles, i.e. $t_{ON(1)} + t_{OFF(1)}$ will alternate with series of short cycles $t_{ON(2)} + t_{OFF(2)}$ as follows, in a ratio of 1 to 2, for instance :

- $t_{ON(1)} + t_{OFF(1)}$
- one series of 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$
- $t_{OFF(1)}$
- a second series of 30 repetitions of $t_{ON(2)} + t_{OFF(2)}$
- $t_{OFF(1)}$
- and then, coming back at $t_{ON(1)} + t_{OFF(1)}$

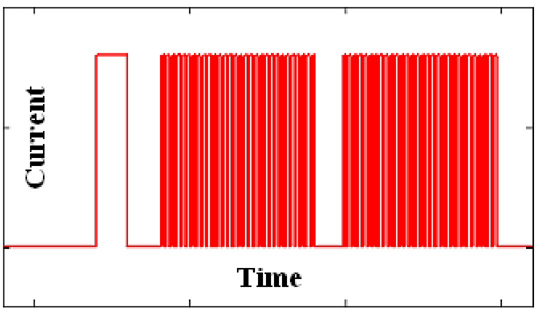

Fig. 7: long cycles and short cycles alternations

We can consider that if the heating of the fuse is the same after 1 hour than after 5 min. (and idem at cooling down), then from the point of view of damage, a long cycle $t_{ON(1)} + t_{OFF(1)}$ is equivalent to a short cycle $t_{ON(2)} + t_{OFF(2)}$.

Then:

$$\begin{aligned}&\mathrm{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= \mathrm{Damage}(t, A_{(1)}) + \mathrm{Damage}(t, A_{(2)})\end{aligned} \tag{9}$$

and:

$$\text{" f " = " + "} \tag{10}$$

But if the heating of the fuse is different between long and short cycles, then, from the point of view of damage, a long cycle $t_{ON(1)} + t_{OFF(1)}$ is not equivalent to a short cycle $t_{ON(2)} + t_{OFF(2)}$. And the question will be how much each of them will contribute to the ageing of the fuse.

Because of long cycle $t_{ON(1)} + t_{OFF(1)}$, at the time t, the fuse will present the damage :

$$\mathrm{Damage}(t, A_{(1)}) = \frac{N(t, A_{(1)})}{Nr(A_{(1)})} \tag{11}$$

and because of short cycle of $t_{ON(2)} + t_{OFF(2)}$, at the same time t, the fuse will present another damage :

$$\mathrm{Damage}(t, A_{(2)}) = \frac{N(t, A_{(2)})}{Nr(A_{(2)})} \tag{12}$$

The actual life-duration t_{end} of the fuse will be reached when the summation of damages will be :

$$\begin{aligned}&\mathrm{Damage}(t_{end}, A_{(1)}) + \mathrm{Damage}(t_{end}, A_{(2)})\\&= \frac{N(t_{end}, A_{(1)})}{Nr(A_{(1)})} + \frac{N(t_{end}, A_{(2)})}{Nr(A_{(2)})} = 1\end{aligned} \tag{13}$$

If we draw the characteristic curve of $\mathrm{Damage}(t, A_{(2)})$ vs. $\mathrm{Damage}(t, A_{(1)})$:

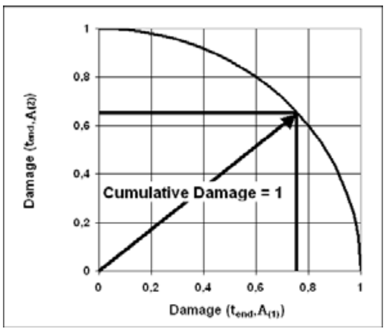

Fig. 8: Damage(t_{end} , □(2)) vs. Damage(t_{end} , □(1))

we'll get the equation of a circle and global damage will be the result of a quadratic summation:

$$\begin{aligned}&\mathrm{Damage\_cumulative}(t, A_{(1)}, A_{(2)})\\&= \sqrt{\mathrm{Damage}^2(t, A_{(1)}) + \mathrm{Damage}^2(t, A_{(2)})}\end{aligned} \tag{14}$$

and:

" **f** " = " **quadratic summation** "

This expression will be highly useful in any case of combination of independent (or non-linear) stresses. It will be used to calculate the life duration of a fuse from the stresses expressed as $A_{(1)}$ and $A_{(2)}$. Reversely, it will be used in order to determine the right fuse for supporting during 10 or 30 years a combination of stresses expressed as $I_{ON(1)}$, $t_{ON(1)}$ + $t_{OFF(1)}$ and $I_{ON(2)}$, $t_{ON(2)}$ + $t_{OFF(2)}$.

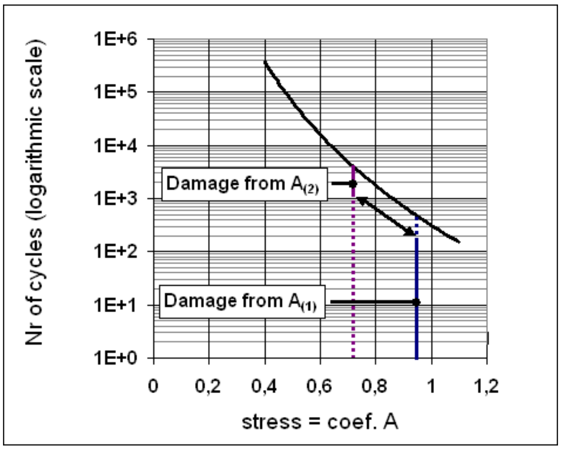

Fig. 9: in words of damage, Damage(t_{end} , ⍰$_{(1)}$) is about 2/3rd and Damage(t_{end} , ⍰$_{(2)}$)is about 1/3rd ; but in words of Nr of cycles, Nr(A(1)) is about 200 cycles and Nr(A(2)) is about 2400-1000=1400 cycles.

Before coming to conclusions, it is to be noticed that the quadratic summation is available when two or more independent cycles are combined and only in this case. By non-independent combinations we understand cycles showing for instance different conduction phases :

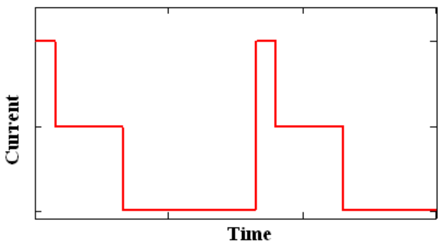

Fig.10: an example of combination of two conductive phases within a cycle. This combination does not allow to use the quadratic summation to evaluate the life-duration of the fuse.

In case of non-independent cycles, it should be advised to determine a more pessimistic cycle. The idea of cumulative damage is not available.

5. Conclusions

Even with many experiments, the calculation of the life-duration of ultra-fast fuses is always a demanding exercise. Many and many tests have been and are still run by manufacturers, but unfortunately, tests cannot cover the whole range of customers' applications. A strong difficulty is that customers intend to use fuses for many years when they are requiring for immediate answers. The authors hope that this paper will be an efficient contribution to the matter and will help engineers facing ageing of equipments.

In addition, we would like to underline some interesting points :

- first is that cumulative damage has been presented here-above, considering the coefficient $A = \frac{I_{RMS}}{In}$ used by MERSEN's engineers ; of course, same equivalent and appropriate demonstration could be done for any other parameters comparable to a stress ;
- damage has been defined by a linear law :

$$\mathrm{Damage}(t) = \frac{N(t)}{Nr} \qquad (7a)$$

  it should be interesting to study and compare this law with a logarithmic law :

$$\mathrm{Damage}(t) = \frac{\log[N(t)]}{\log[Nr]} \qquad (16)$$

  this is to be connected with the idea of C.O.D. presented in the first paragraph of this paper ;
- the quadratic summation can be extend to more than 2 independent cycles :

$$\mathrm{Damage\_cumulative}(t, A_{(1)}, \ldots A_{(i)}, \ldots A_{(n)}) = \sqrt{\sum_{i=1}^{n} \mathrm{Damage}^2(t, A_{(i)})} \qquad (17)$$

- the cumulative damage method has been presented considering the mean values of the life-duration ; extension to the Gaussian distribution around these mean values is also possible.

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