

OVERLOAD TESTS FOR FUSES IN ROLLING-MILLS

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Summary

Recently the authors were involved in the solution of problems related to frequent premature operation of fuses for the protection of rolling-mills used in the lamination of steel ingots which are subjected to frequent overload currents.

Based on this experience and existing literature, some applications and typical circuits are presented including a description of the inherent thermal and dynamical effects. Standardized tests and their comparison with actual situations are described. Finally, in order to facilitate the user some suggestions are given to improve the current technical standards.

1. Introduction

Being an equilibrium point between users and manufacturers, international standards represent the state of the art of products and have a very large number of readers all over the world.

Due to the very big number of specific situations that they shall cover it is not always possible to describe in a sufficiently clear way to the medium reader, the fundamentals/objectives of some of the specifications, which are clear to the experts during the preparation of the standards.

It is a natural fact that the higher the development of one country in one knowledge area the bigger is its concern regarding to the participation in the elaboration of the standard.

Even when not participating many other countries will use these documents in the whole or as the main reference for the national ones, sometimes without a good understanding of the extent.

In a certain way this is the main reason for this paper in which it is tried to resume in an easy way to the user some aspects related to overload cycles inherent to the application of fuses in the protection of circuits involving semi-conductors, in particular for the protection of variable speed dc motors used in the rolling of steel ingots.

For these fuses it is very important to the user to supply the manufacturer with the correct informations about the actual use.

Only with these informations it is possible to the manufacturer to indicate the adequate fuse avoiding

consequences as fast deterioration of the fuse-element, premature operation and bad performance when the fuse operates in severe failures.

For the good understanding of the text it is valuable to resume some definitions as used in IEC Publication 269-4:

- a) Pulsed current - an unidirectional current the instantaneous value of which varies cyclically and includes intervals of small values of current as in Figure 1.
- b) Rated-current - a value assigned by the manufacturer and verified by temperature rise and repetitive duty tests.
- c) Tests for the verification of rated current - composed of a temperature rise test at rated current of the fuse and one test consisting of the application during 100 h of a cycle with an on-period of the conventional time with 1.05 rated current and an off-period of 10% the on-period.
- d) Overload tests - a test in which the fuse is subjected to 100 load cycles, each having a total duration equal to 0.2 the conventional time. The currents and durations are based on the conventional overload curve to be verified. The "on" periods have a current value and duration corresponding to the coordinates of the curve, the "off" forming the rest of interval.

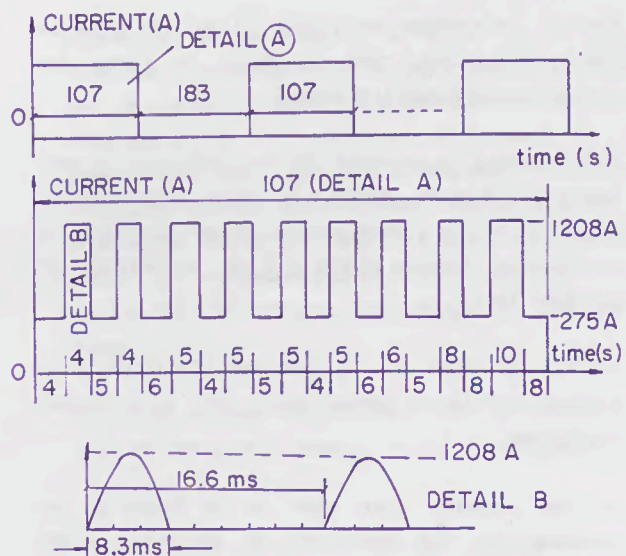


FIGURE 1- ACTUAL CYCLE IN A FUSE FOR ROLLING-MILLS.

2. Typical Application of Fuses in Rolling-Mills

One typical application is shown in Figure 2. Currents/cycles as in Figure 1 may be applied to the fuses about 10^5 times per year. In Section 4 a comparison is made between the actual cycle and the conventional overload cycle for overload tests.

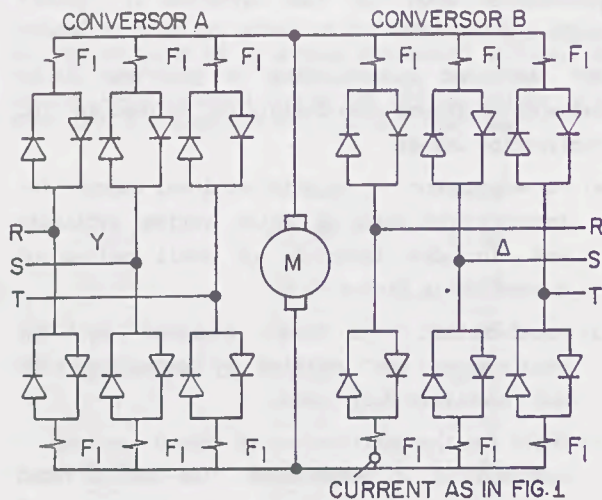


FIGURE 2-TYPICAL APPLICATION OF FUSES IN ROLLING-MILLS.

3. Thermal and Dynamical Effects of Overloads

Both effects conduct to ageing during these fuses life as the overload currents are the usual ones and considerably greater than the rated current I_N (3 up to 6 I_N).

3.1 Thermal Effects

Several references among them [1] and [2] describe the thermal effects that may occur in fuses for semi-conductors applications.

They present approaches on the influence of many factors as type of materials, sand compactation, rigidity of the fuse-elements, values and duration of overload, looking always for the estimation of the fuse life.

In all of them it is not possible to define a general calculation method valid for all general conditions.

To the readers that want to go deeper in the fundamentals of the behaviour of materials under cyclic loading at low and high temperatures

references [3] to [5] are plenty of useful informations. In these references the processes of fatigue, creep and crack propagation inherent to the materials are described under several points of view. Basically the common objective is also how to predict the service life of materials and/or components considering temperatures, cycles and frequency of application, mean stress applied, environment, finishing of materials, tests, elastic stresses distribution around a notch and others. It can be seen that general formulas are not also available for simultaneous conditions. One resume of the more relevant points from these references as they were interpreted by the authors is in the lines below.

Every time one material (or a part of one equipment) is subjected to compression or tension stresses strains are produced. These strains may be elastic with the material, from the macroscopic point of view, returning to its original dimensions after the end of stress or plastic when one limit is exceeded. In this case the material after the end of the stress does not recover its previous dimensions. The effect can be seen by an hysteresis curve as in Figure 3.

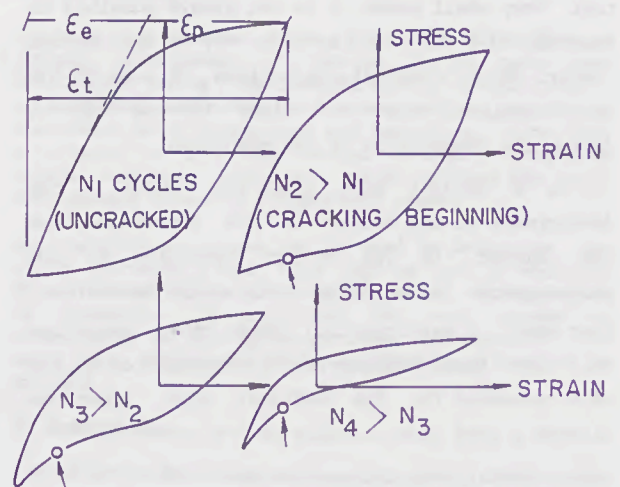


FIGURE 3-TYPICAL HYSTRESIS LOOP DURING CYCLING TEST SHOWING CRACK INDICATIONS.

From the microscopic point of view if one material is perfectly plain and a percentage of the elastic limit is not exceeded, stress cycles could be applied indefinitely without reduction of the life.

As this does not occur materials may exhibit fatigue characteristics due to the propagation of a

surface microcrack from some initial defect or flaw. If the cyclic stress level is sufficiently high the microcrack will spread across the surface and penetrate into the body by continuing to-and-from slip processes until it has reached such a size that it is able to grow as a macrocrack, that is, its growth will depend on the amount it opens and closes under the normal cyclic stress across its faces.

A fuse subjected to an up and down current may be seen as a beam fixed in the two ends (Figure 4). When the current and consequently temperature increases the length of the element tends to increase. As the ends are fixed the internal stresses increase leading eventually to the rupture of the element (if it is very rigid). When the current is lowered the temperature and the length decreases. The repetition of the processes is exactly what is shown in Figure 3 and the consequence is the propagation of microcracks along the time.

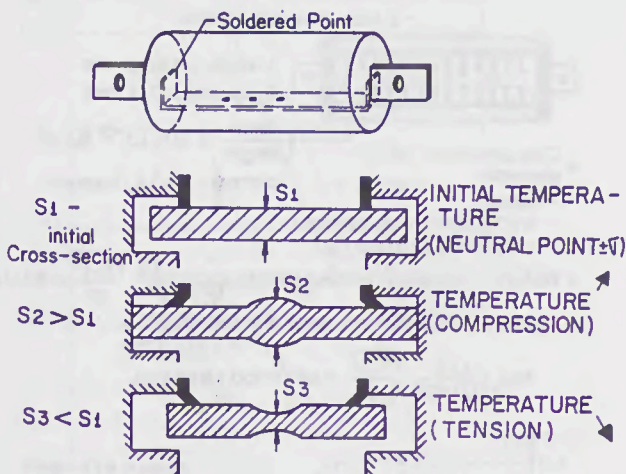


FIGURE 4 - FUSE - MECHANICAL SYSTEM X VARIATION IN TEMPERATURE

This could also be seen as if in each cycle one small plastic strain is retained and is "added" to the previous one up to the point of rupture.

In reference [1] a good description is made on how to minimize the stresses increasing the life by reducing the rigidity of the fuse element. It is also stated that fuse elements without bends shall not be used.

In the literature whichever is the application of

the material the estimation of the life is based in stress-strain and thermal tests and leads to a formula of the type:

$$N^\alpha \cdot \epsilon_p = C \quad (1)$$

where N is the number of load cycles up to failure (as in Figure 3), ϵ_p is the plastic strain, C is a constant dependent on the temperature taking for a fixed one the form of:

$$C = \frac{1}{2} \epsilon_f = \frac{1}{2} \ln \left(\frac{1}{1 - \beta} \right) \quad (2)$$

ϵ_f being the fracture ductility and β the percentual reduction in cross-sectional area when the rupture occurs after a fatigue test at a specific temperature as in Figure 3.

The higher is the test temperature the lower is C . It shall be mentioned that the plastic strain (ϵ_p) is the difference between the total strain (elastic + plastic) and the elastic one (ϵ_e). In the case of fuses the total strain is:

$$\epsilon_t = \beta \cdot \Delta\theta \quad (3)$$

- the temperature coefficient and $\Delta\theta$ the temperature difference.

For this reason it is not very good to assume for calculations that the plastic strain is nearly equal to the total strain specially when the ratio overload/rated current is not high. In these cases the plastic strain may reach insignificant values.

Concerning to the constant α , we go to the point that the literature mentions two types of processes as in Figure 5. When low endurance are involved, lets say $N < 10^4$, the fatigue process is the predominant one. For long endurance ($> 10^7$) creep processes are the relevant ones. Values of α to be considered are in the range 0.3 up to 0.5 (the most used) for low-temperatures fatigue and from 0.6 up to 1.0 for high-temperature-fatigue in the creep range.

For these reasons expressions for prediction of life as the useful example showed in Reference [2]:

$$N = \frac{1}{(\beta \cdot \Delta\theta \cdot m)^2} \cdot \left(\frac{C}{K} \right)^2 \cdot \left(\frac{1}{S^2} \right)^2 \quad (4)$$

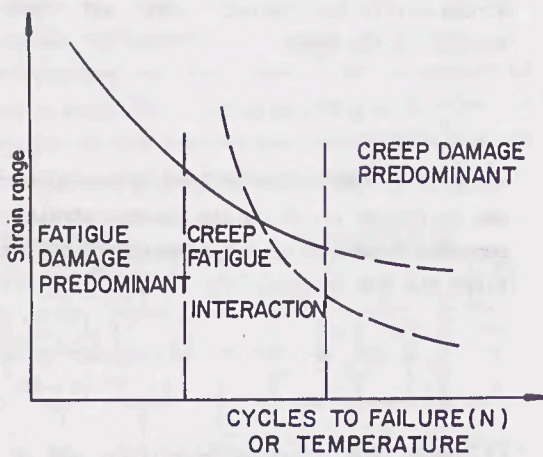


FIGURE 5 - PREDOMINANT PROCESSES TO FAILURE

where $\Delta\theta_m$ is the temperature rise of the melting point, K - factor to consider the rigidity of the fuse-element and S - ratio between overload-current and current from the melting-time characteristic for the same pulse duration, shall be used with special attention for the conditions that they are developed from assumptions as $\alpha = 0.5$ and $\Delta\theta = \Delta\theta_m \cdot S^2$ for any value of S and consequently temperature.

The effects of local concentration of stresses due to the existence of notches and of the mean value of the applied stresses (function of the higher and lower temperatures during the cycle and not only of the difference) may be seen by expressions like:

$$\sigma_{nm} = \frac{\sigma_0}{Kt} \left(1 - \frac{\sigma_m}{\sigma}\right) \quad (5)$$

where:

σ_{nm} - the nominal notched fatigue strength, at a given endurance N

σ_0 - the plain (without notches) fatigue strength at zero mean load (as in Figure 3) at the same endurance

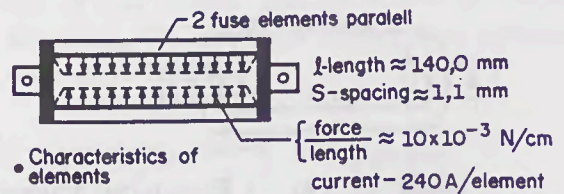
σ_m - the applied nominal tensile mean stress

σ - the tensile strength of the material

K_t - geometric elastic stress concentration factor = σ_{notch}/σ applied

3.2 Dynamical Effects

In the used references there were no specific details about these effects but it is a known phenomena that the circulation of currents in neighbour conductors generate electro-dynamical forces/stresses as in Figure 6, the way as these forces will stress the "fuse-element beam" dependent on the ratio between the natural frequency of the beam and the frequency of the overload current. As the natural frequency changes with the span length and there are several micro-span formed by conductor-sand grain it is reasonable to assume that even when the dynamical forces are not high they actuate in parallel fuse-elements forming a high frequency vibrator and trying to reduce the distance between them. Along the time the tendency is that more and more it will be difficult for the fuse-element to recover to its original dimensions and consequently giving a contribution for the growth of cracks.



- Characteristics of elements
 - silver
 - 6x0,3mm (cross-section)
 - weight - 0,2 kg/cm (gt)

- Natural frequency (without sand) = $f_{01} = \frac{112}{l^2} \frac{\sqrt{E \cdot J}}{gt} \approx 43 \text{ Hz}$

- Natural frequency (with sand $\phi 1 \text{ mm}$) = $f_{02} = \frac{112}{2(l/140)^2} \frac{\sqrt{E \cdot J}}{gt} \approx 140^2 \cdot f_{01} = 845 \text{ kHz}$

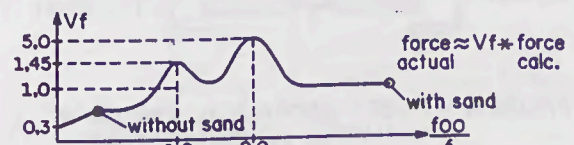


Figure 6 - Electro-dynamical stresses

Maybe this aspect explains one statement in Reference [1] about the increase in the thermal stability of some tested fuses when the sand compactation decreases, in despite of the poorer heat exchange through the sand.

4. Standardized Tests and Comparisons with Actual Situations

In IEC Standard 269-4 it is specified one test related to overloads as explained in Section 1 of this paper.

This text is used only to verify if overloads within the limits of the conventional overload curve supplied by the manufacturer can be applied to the fuse 10^2 times without problems.

If the actual duty cycle of a fuse is known then, it is possible by transforming the actual duty in an equivalent conventional one to know by comparison with the conventional overload curve if the fuse is adequate to the 10^2 cycles.

The conversion is done by integrating I^2t (actual) along 0.2^* conventional time, and using the maximum value of actual current (I_{max}). The "on" period duration is equal to I^2t (actual)/ I_{max}^2 .

As an example we will take one fuse rated $I_N = 500$ A with pre-arcing and conventional overload curves as in Figure 7 and an actual duty cycle in service as in Figure 1.

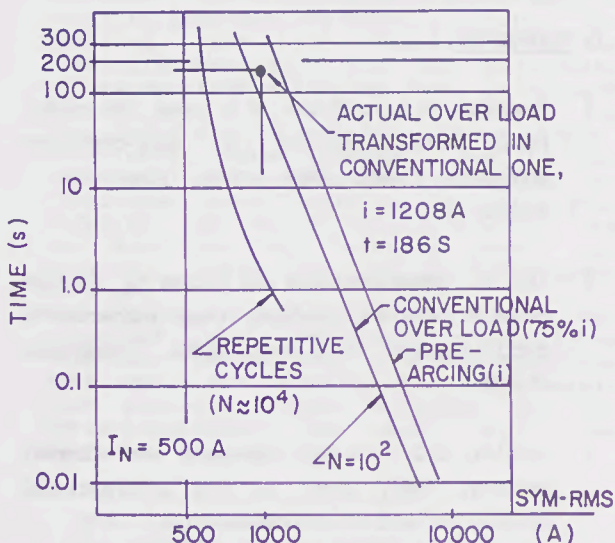


FIGURE 7 - EXAMPLE OF OVER LOAD CURVES ($N=10^2$ - $N=10^4$)

To convert the actual cycle in a conventional one it is necessary to integrate I^2t (actual) along $0.2 * 4 h = 48$ min. This integral is around $27,60 * 10^6 A^2.s$.

As the maximum actual current is 1208 A the "on" time for the conversion to conventional cycle would be $t_{on} = 27 * 10^6 / 1208^2 = 180$ s and the "off" period would be $48 * 60 - 180 = 2700$ s.

If we go to Figure 7 it can be seen that 1208 A can be applied on fuse during approximately 20 s 100 times.

As the obtained point is to the right side of the conventional overload curve the fuse would probably melt before 100 cycles. An adequate fuse to resist more than 100 cycles should have a higher rated current in this case.

The main problem in this actual example of a fuse protecting one very big slab mill is that the actual cycle may in certain occasions occur around 10^4 times per month or 10^5 per year and for this 500 A fuse the "informed $N = 10^4$ overload curve" is as in Figure 7, although the experience in use indicates higher values of N.

5. Proposals for Improvements in Standards

Taking into account all the observations in the previous paragraphs it can be stated that the great number of informations which the user shall supply the manufacturer to obtain the appropriated fuse are normally, in the first moments, out of the understanding of the medium user.

Improvements in the standards are necessary in order to facilitate the user and to avoid waste of money and time until the understanding of the reasons for frequent failures leads to the satisfactory solution.

Some suggestions for inclusion in IEC 269-4 are:

- a) to include a note concerning to the 100 cycles overload test mentioning that the test itself provides only a relative comparison between fuses of different manufacture, but gives, in the present state of the art, no real indication of the ability of the fuses to withstand a very large number of pulses during their service life. By that it is meant that the conventional overload curve is only applicable to an occasional pulse situation, where in the lifetime of the fuse-link it will only be subjected to a small number of such overloads
- b) to include one statement mentioning that when required the manufacturer may provide additionally to the conventional overload curve (10^2 pulses), overload curves for 10^4 and 10^6 pulses (without the inclusion of a test for verification)
- c) to reevaluate the conventional overload test

method as the values of t (on) and t (off) are very different from the actual cycle (compare Figure 1 with transformed curve in Section 4). The much higher values of t (off) in the conventional cycle may generate a mean value of the applied stresses (see Equation 5) much lower than the actual one.

Maybe this is one part of the explanation for a fact that is occurring with one test that is still running giving unexpected results.

One fuse of the type in Figure 7 is being subjected to a continuous cycle as in Figure 8 in the last months. After 17000 cycles the resistance of the fuse and the temperature rise of the end caps which are under measurement from the beginning did not show variations greater than 11%. The test will run until the fuse melts.

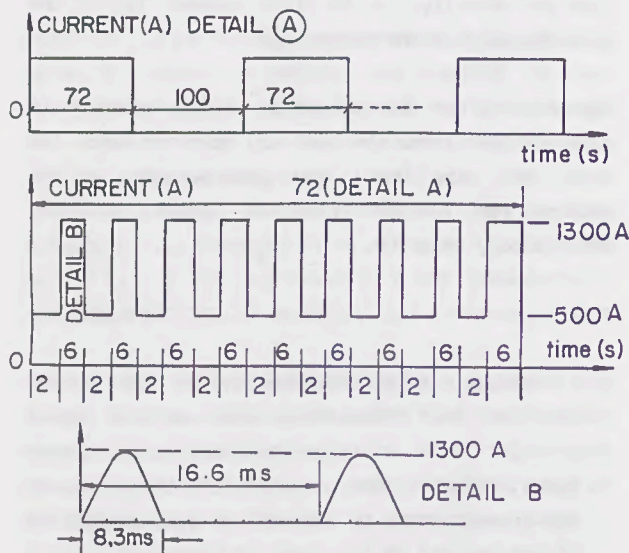


FIGURE 8 - CYCLE FOR TEST RUNNING FOR FUSE IN FIG.7.

6. CONCLUSIONS

When we started to develop this work, based on previous experiences with frequent fuses failures the purposes were in addition to clarify some aspects to fuses users, to better understand the reasons for the failures and also to propose some calculation method for evaluation of fuse life under overload conditions. After consultation to the referred literature and some studies a good experience was reached.

It was not possible to obtain the calculation

method and we think that now with a better understanding of the parameters involved this is very difficult and a task for manufacturers which shall involve at the same time electrical engineers and experts actuating in materials^{3,4,5}.

We think that the objective of reporting in easy words the aspects related to overload in fuses was reached up to the point of our limited knowledge on the subject.

The main conclusion was that if this subject is still not very clear for us after the end of the work, it is much more difficult for the medium user to know and to evaluate the informations to be supplied to the manufacturer to specify or to replace a fuse for the applications in the scope of this paper. By this reason we are sure that the proposals for improvements in standards are valid and have space for consideration from the experts in this subject.

7. REFERENCES

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