ASSESSMENT OF COMPLEX LOADING CYCLES AND ESTIMATION OF FUSE LIFE

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Abstract : A new method of estimating the thermal response of fuses to complex loading cycles is described. The method is based on the use of the fuse transient thermal impedance, which can be estimated simply from its time-current characteristic. A procedure for estimating the rate of deterioration and hence the life is described, based upon the number and magnitude of straining events within a given cycle.

I. INTRODUCTION

The long-term effects of thermal fatigue must be taken into account when selecting fuses for applications which have repetitive cyclic loads. This is particularly important with semiconductor fuses [1,2] which have small and fragile notches in their fuse elements.

Test data is normally obtained with a simple ON/OFF loading cycle such as that shown in Fig.1.

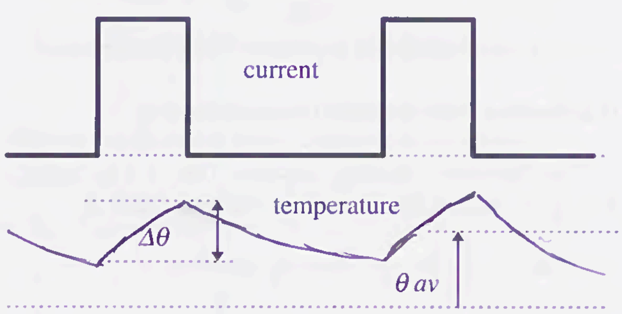


Fig.1 Fuse response to simple repetitive cycle.

For this cycle the best way to assess its severity is to compute the peak-to-peak temperature excursion $\Delta\theta$ and the average temperature θav of the hottest notch using a finite-difference or finite-element model to compute the fuse response. The number of cycles to failure can then be estimated using eq.(1), which is derived directly [2] from the Manson-Coffin law of mechanical fatigue.

$$N = \frac{K_\theta}{\Delta\theta^{P}\,\theta_{av}^{\,Q}} \qquad (1)$$

The life is strongly affected by $\Delta\theta$, which produces a proportional thermal strain in the fuse element, but is only weakly dependent on θav. The constant K_θ depends on the mechanical construction of the fuse. P, Q and K_θ must be determined from test data by regression analysis.

Finite-difference or finite-element modelling programs are useful for special projects or investigations. However they require the full physical construction of each fuse to be supplied as data and the computations are too time-consuming to be incorporated into routine fuse selection programs, even using the fastest modern computers.

Routine selection of fuses for cyclic duty is often based upon the fuse time-current characteristic. For example, with a simple ON/OFF cycle, it may be required that the ON current does not exceed a certain fraction of the current which produces melting in a time equal to the ON time [3].

However, real applications very rarely use a simple ON/OFF cycle. Repetitive industrial processes have cycles consisting of several blocks of current at various levels and with durations from seconds to hours. Traction applications have even more complex loading profiles, which cannot be represented by an equivalent ON/OFF cycle. The cycle shown in Fig.1 contains only one **straining event** (strain reversal) within it, whereas a complex cycle may contain several such events, of different magnitudes, each of which contributes to the degradation of the fuse. The first step in assessing these cycles is to calculate the fuse thermal response, and a simple method for doing this, based upon the time-current characteristic, is given below.

II. TRANSIENT THERMAL IMPEDANCE

The temperature response of diodes and thyristors to complex loading cycles has been calculated for many years using the transient thermal impedance curve, which is published for each device. This curve relates the device hotspot temperature to the power input, as follows :

$$\theta(t) = Z(t)P \tag{2}$$

$Z(t)$ is a function which increases from zero at $t=0$ to a steady-state final value Z_{ss}. Using the same concept for a fuse, for a one-shot melting test from room temperature,

$$\theta_m = Z(t_m) R_m I_m^2 \tag{3}$$

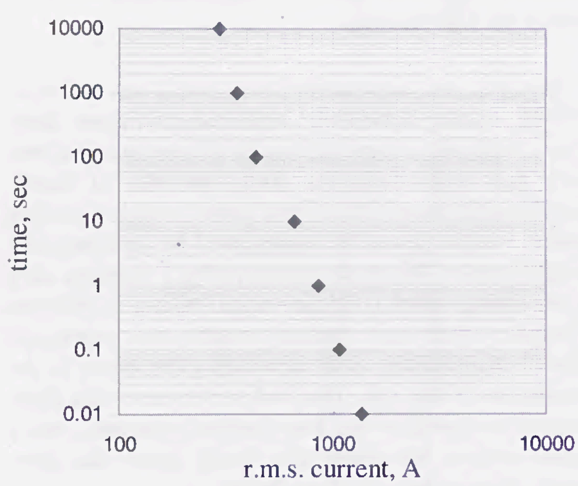
where

θ_m = temperature rise up to melting point
t_m = melting time
I_m = current which produces melting in a time t_m
R_m = average fuse resistance during the melting period

Use of the average value R_m is an approximation, since the fuse power actually increases with temperature due to the positive temperature coefficient of the element metal. The average resistance over the melting period will vary with the waveshape of the temperature-time transient, but will typically be about 2.4 times the value at 20C.

The transient thermal impedance is then given by :

$$Z(t_m) = \frac{\theta_m}{R_m I_m^2} \tag{4}$$



Fig, 2 Typical time-current characteristic

II.1 Normalization

Assume that the 10000s point on the time-current curve represents a steady-state thermal condition and take the current at this point (I_∞) as a reference (base) value. This then gives

$$Z_{ss} = \frac{\theta_m}{R_m I_\infty^2} \tag{5}$$

Dividing (4) by (5) gives the normalised transient thermal impedance $f(t)$ as

$$f(t) = \frac{Z(t_m)}{Z_{ss}} = \left[\frac{I_\infty}{I_m}\right]^2 \tag{6}$$

$f(t)$ increases from 0 to 1 as time increases from zero to infinity, and the curve can be derived very simply from the fuse time-current characteristic. Fig.2 shows a typical time-current characteristic for a fast-acting fuse and Fig.3 shows the derived normalised transient thermal impedance curve. For each time value on Fig.2 the corresponding melt current I_m is known, and then the corresponding value of $f(t)$ is calculated using (6).

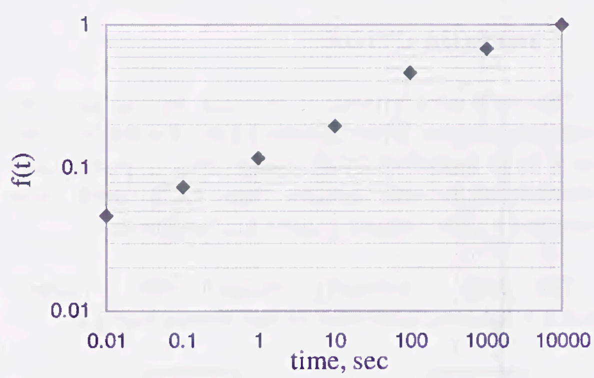


Fig.3. Transient thermal impedance derived from Fig.2

II.2 Heating from an initial temperature θ_0

The previous heating history (for $t < 0$) gives $\theta_0 = Z_{ss} P_0$ and so, for an average fuse resistance R,

$$\theta(t) = \theta_0 + (P - P_0)Z(t)$$

$$\theta(t) = \theta_0 + (I^2 R - \frac{\theta_0}{Z_{ss}})Z(t)$$

$$\theta(t) = \theta_0[1 - f(t)] + I^2 R Z_{ss} f(t)$$

This can be normalised by dividing by $\theta_m (= R_m Z_{ss} I_\infty^2)$ to give the per-unit temperature rise as

$$\bar{\theta}(t) = [1 - f(t)]\,\bar{\theta}_0 + \alpha \bar{I}^2 f(t) \tag{7}$$

where the bar indicates a normalised (p.u.) value. Temperature is expressed as a fraction of the temperature rise to melting while current is a multiple of the 10000s current I_∞. $\alpha = R/R_m$ and is the ratio of the average fuse resistance during the heating period to the average resistance from room temperature to melting.

II.3 Response to a multipart cycle

Consider a cycle with N blocks of current as shown in Fig.4. During each block the r.m.s. current is constant.

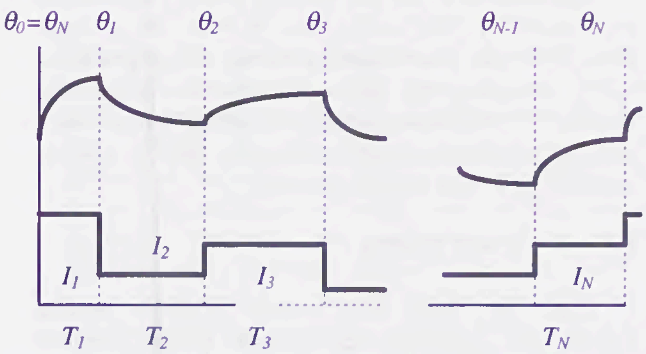


Fig.4 Fuse response to a complex loading cycle

Writing $f(T_1) = f_1$ and applying (7) to each of the blocks in turn gives

$$\bar{\theta}_1 = (1-f_1)\bar{\theta}_N + \alpha f_1 \bar{I}_1^2$$

$$\bar{\theta}_2 = (1-f_2)\bar{\theta}_1 + \alpha f_2 \bar{I}_2^2$$

$$\bar{\theta}_k = (1-f_k)\bar{\theta}_{k-1} + \alpha f_k \bar{I}_k^2$$

...

This can be rewritten as the cyclic matrix equation

$$\begin{bmatrix} 1 & 0 & .. & 0 & -(1-f_1) \\ -(1-f_2) & 1 & .. & 0 & 0 \\ 0 & -(1-f_3) & .. & 0 & 0 \\ 0 & 0 & .. & 1 & 0 \\ 0 & 0 & .. & -(1-f_{N-1}) & 1 \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \\ \bar{\theta}_3 \\ \\ \bar{\theta}_N \end{bmatrix} = \alpha \begin{bmatrix} f_1\bar{I}_1^2 \\ f_2\bar{I}_2^2 \\ f_3\bar{I}_3^2 \\ \\ f_N\bar{I}_N^2 \end{bmatrix}$$

which can be solved for the temperatures at the ends of each of the time blocks ($\bar{\theta}$ ...). The square coefficient matrix is very well conditioned.

The ratio of average fuse resistance within each time block to the average resistance during a melting test for this time actually varies from block to block, but in this simplified analysis an average value of α has been used, assumed to apply over the whole cycle. α then appears in the equations as a simple scaling factor. The temperatures can be initially calculated with α=1 and then scaled down as desired.

The resulting system of equations is linear. If very high currents are input the resulting per-unit temperatures can exceed 1, which corresponds to a value higher than the melting point. This is not allowable and can be dealt with by testing the results after the solution.

After the values of $\bar{\theta}$ have been found, the actual shapes of the temperature waves within a current block can be calculated if desired using (7). However the waveshapes within a block are not needed in practice, just the temperatures at the start and finish of the block.

II.4 Counting the number of straining events

If a **straining event** is defined by a transition from a PEAK to a TROUGH on the temperature-time wave, examination of many different cyclic temperature waves has shown that within any cycle with *N* blocks there is a minimum of 1 and a maximum of *N/2* straining events. An example is shown in Fig 5 below.

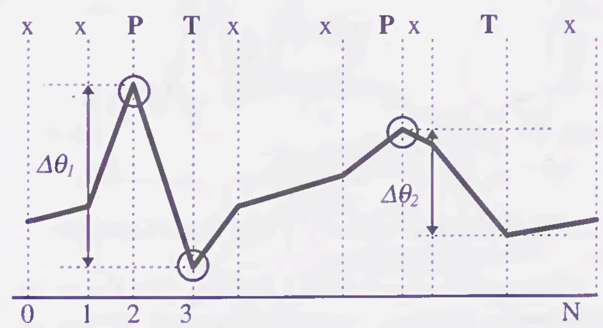


Fig.5 Temperature response with peaks and troughs

The response shown in Fig.5 contains 2 straining events with magnitudes $\Delta\theta_1$ and $\Delta\theta_2$. In general the number and magnitude can be found by the following algorithm :

a) scan all transition points and mark peaks with a 'P' and troughs with a 'T'. Otherwise mark with an 'x'. The number of straining events is equal to the number of peaks (or troughs).

b) scan a second time and calculate the peak-to-peak temperature differences between each peak and the next trough ($\Delta\theta_1$, $\Delta\theta_2$ ...).

There is an ambiguity here, depending upon whether $\Delta\theta$ is defined at the difference between a peak and a subsequent trough or vice-versa. i.e. 2 straining events within a cycle can be defined in 2 different ways. In this paper the start of an event is defined as the first peak or trough encountered within a cycle.

II.5 Typical results

Fig. 6 shows the per-unit temperature (lower graph) response calculated using the normalised transient impedance curve of a 350A fuse used in a traction application. The current loading (upper curve in Fig.6) in this case was taken directly from measurements on a railway locomotive at 5 minute intervals over a 24-hour period, giving a duty cycle with 288 blocks of current.

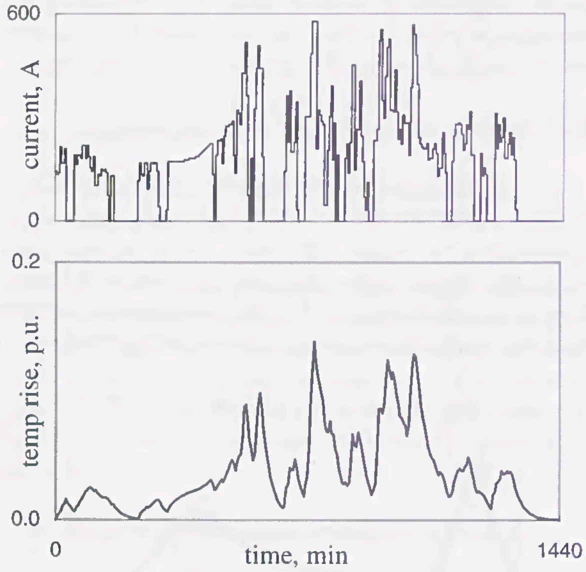


Fig.6 Thermal response of fuse to traction cycle

Although the cycle shown contains 288 blocks, the temperature response curve contains only 29 straining events.

III. ESTIMATION OF FUSE LIFE

The average temperature rise of the fuse is assumed to depend on the r.m.s. current loading (as a fraction of the rated current), according to a power law. With this assumption eq.(1) becomes

$$N = \frac{K'}{\Delta\bar{\theta}^{\,P}\,\bar{I}_{rms}^{\,Y}} \tag{8}$$

For a simple ON/OFF cycle the **rate of deterioration** can be defined as the reciprocal of the number of cycles to failure. The rate of deterioration is therefore

$$r = \frac{1}{K'}\,\bar{I}_{rms}^{\,Y}\,\Delta\bar{\theta}^{\,P}$$

For a multipart cycle each straining event contributes to an increase in the rate of deterioration, according to its magnitude, and so the total rate is

$$r = \frac{1}{K'}\,\bar{I}_{rms}^{\,Y}\left[\Delta\bar{\theta}_1^{\,P} + \Delta\bar{\theta}_2^{\,P} + \ \ldots\right]$$

and the number of cycles to failure becomes

$$N = \frac{K'}{\left[\Delta\bar{\theta}_1^{\,P} + \Delta\bar{\theta}_2^{\,P} + \ \ldots\right]\bar{I}_{rms}^{\,Y}} \tag{9}$$

The value of K' for use with (9) must be determined experimentally. This can be done by tests with a simple ON/OFF cycle. The values of $\Delta\theta$ are calculated using $\alpha = 1$, absorbing the unknown value of α into the constant K'. Alternatively, if finite-difference or finite-element methods are used to calculate the $\Delta\theta$ s, these values can be used directly with (9).

IV. CONCLUSION

Fuses are tested with simple ON/OFF loading cycles, but practical applications usually involve complex loading cycles. An approximate method has been described for evaluating the thermal response of a fuse using a normalised transient thermal impedance curve, derived from the fuse's known time-current characteristic. After the thermal response has been computed, the resulting life can be estimated, based upon the number of straining events produced by the cycle, and their magnitude. The method allows the severity of different loading cycles to be compared.

The main approximation in this method is that the fuse resistance is represented by an average value over the operating temperature range. For adequate life under cycling the peak-to-peak temperature excursions need to be kept relatively low, so this approximation is acceptable. For more accurate analysis full numerical modelling which takes the temperature-dependence of the element metal properly into account, must be used.

V. REFERENCES

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