Endurance of fuses under impulse load

Electrical, thermal and failure behaviour

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Contents

In modern circuits with high current impulses, e.g. for power supply in electro mobility, sudden fatigue of fuses was observed although the applied exposures were far within their specifications. Extensive endurance tests on car fuses showed an accumulation of their individual load history that finally let to failure of the fuse element. It is, however, possible to characterise the observed fatigue behaviour of fuses by a general potential law. This law seem to be generally valid. It can be not only applied to all fuses of the same design but also to any other versions. For this transfer, appropriate rules wereare elaborated.

Motivation

It has been observed time repeatedly during practical applications that fuses may open under certain conditions far before they reach their specified limits. Possible reason for this behavior can be mechanical stresses due to vibration or mechanical extension. But also thermal stresses due to continuous electrical impulse load, leads to fuse element interruptions, which will be the subject of this presentation.

It is therefore intended to cover the physical relationship of the fatigue endurance of fuses under cyclic load as a function of the impulse amplitude and the impulse repetition frequency. In this respect, endurance stands for the amount of impulses before breaking and impulse amplitude is the current square time integral.

It will be emphasised that fuses accumulate their "load history" which means, that previous load impulses weaken the following current-time characteristic of the fuse element noticeably. This observation, similar to the "Wöhler curve" for mechanical stress cycles, must be considered in circuits with alternating load. The results of the research that will be presented here, leads to a calculation algorithm for a fail save design of fused circuits.

Introduction

For its application a fuse can be classified into three different time domains:

short-time -,
mid-time -, and
long-time behaviour.

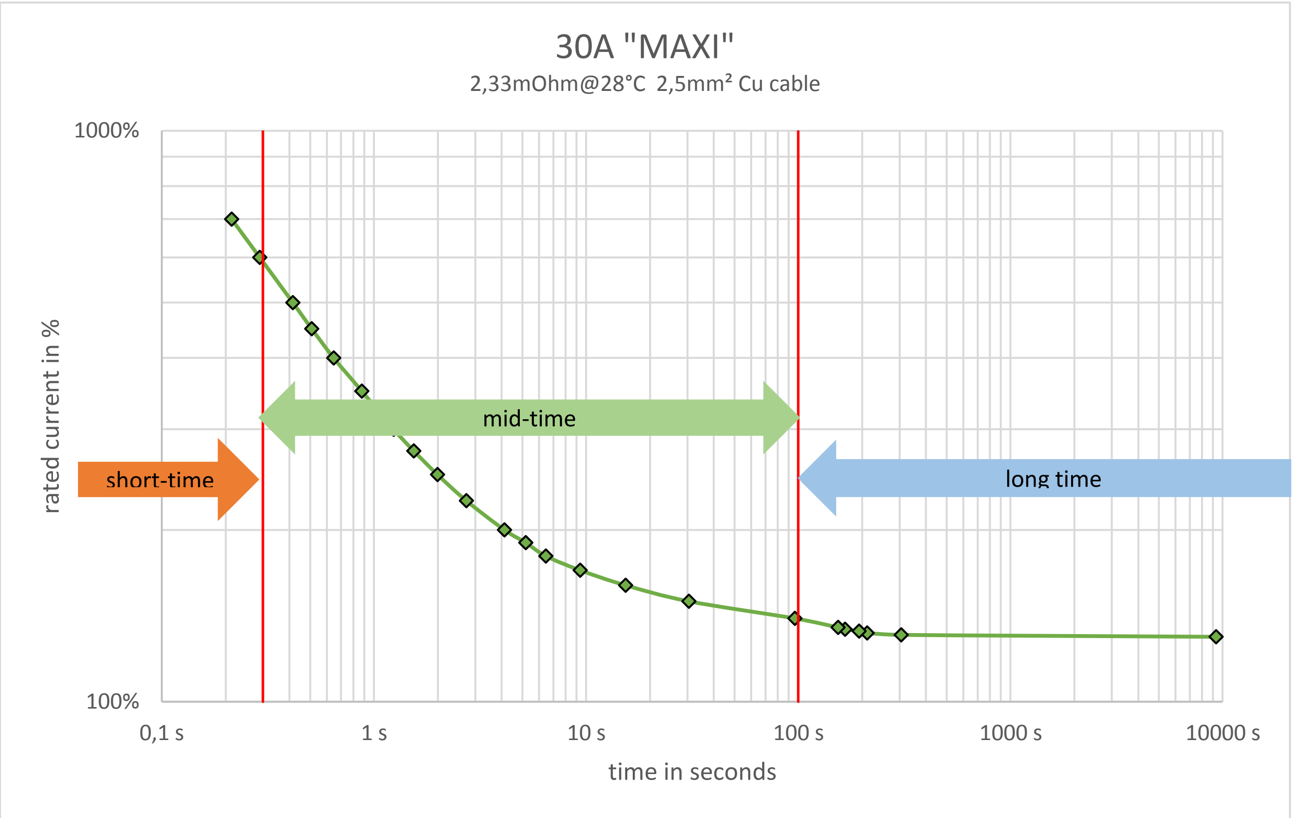


Fig. 1: Time domains of fuses

Each domain is governed by different physico-chemical reactions.

In the **short time domain** the electrically generated heat energy is exclusively collected by the fuse element, which has to be heated up and completely melted in order to open the electrical connection.

In the **mid-time domain** the electrically generated heat energy is to a main part conducted to the end connections of the fuse element. Only a part remains for the fuse element, which also has to be heated up and melted at least in its centre.

In the **long-time domain** the electrically generated heat energy is to a main part dissipated by the surface of the fuse element and to a certain content also conducted to the end connections. Only a part remains for the fuse element, which also has to be heated up and melted at least in the centre. But the opening time of electrical connection is mainly achieved by an oxidation of the surface and therefore by a reduction of the conductor cross section.

However for the endurance of fuses under impulse load the long time behavior is not relevant.

Theoretical Background

1_Current-square time integral.

The critical load for a fuse is the current square time integral:

$$\Theta = \int_0^{\Delta t} I^2 \, dt$$

With:	current square time integral	Θ	in A^2s
	current	I	in A
	impulse duration	Δt	in s

The variation in time of current I can have any shape. If the pulse form is known as a function of time the disconnecting integral Θ can be calculated.

2_Short-time behaviour

The key value to characterize the short-time behaviour of fuses is the fusing integral Θ_f. It defines the amount of Amps square seconds A^2s for disconnecting (heating up and melting) the fuse element.

For short-times the following equation is valid:

$$\Theta = \Theta_f$$

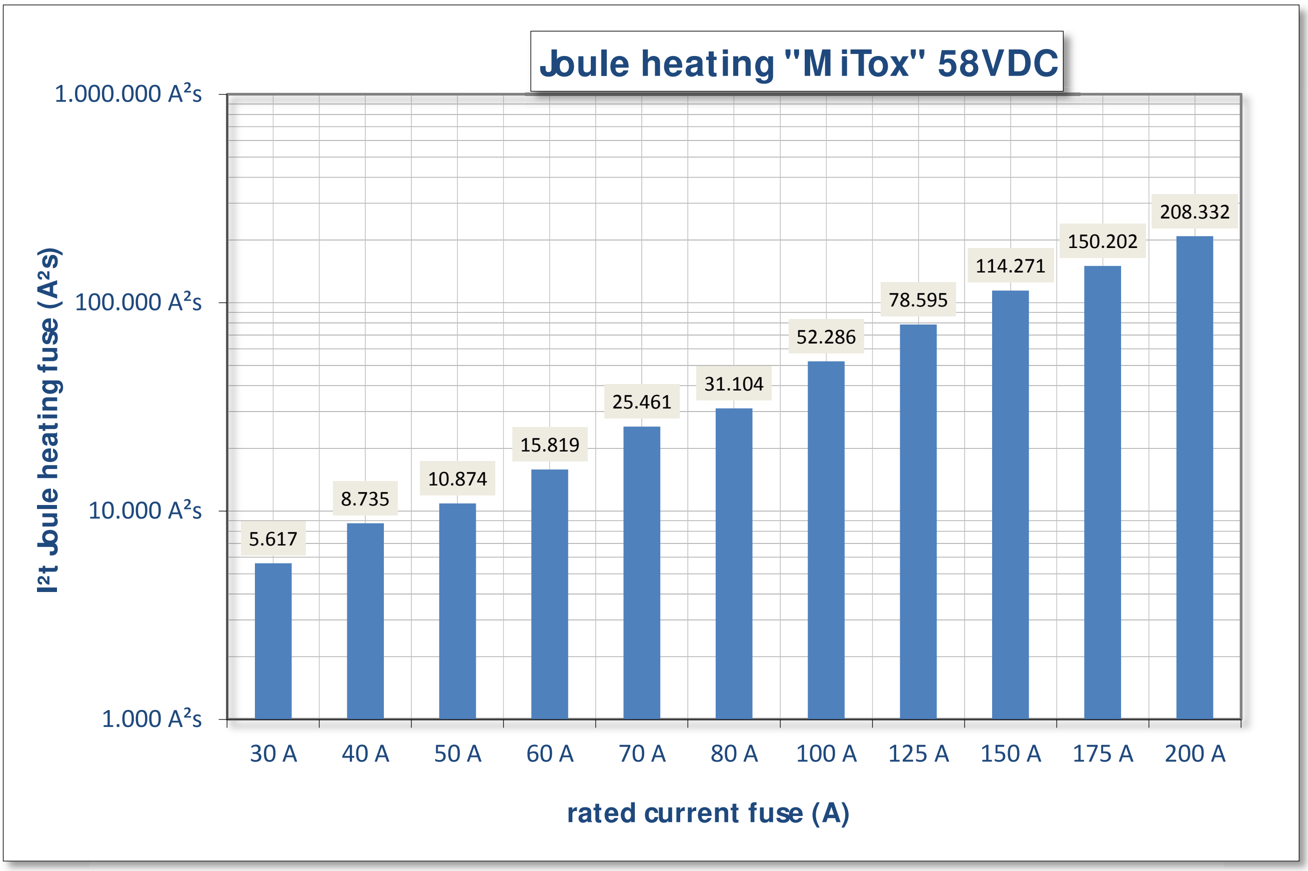
Its value can be measured and also calculated from the material and ambient parameters:

$$\Theta_f = A^2 F$$

With:	cross section	A	in mm^2
	fuse material parameter	F	in $(A/mm^2)^2s$

The following diagram shows the fusing integral Θ_f for the newly designed 58 V fuse MiTox.

In order to keep a safety margin the values are restricted to the heating-up (called Joule heating) of the fuse element to the melting temperature, but excluding the phase shift melting.



3_Operation time for constant current

The operation time t which disconnects is strongly proportion to the square of the current I:

$$t = \frac{\Theta_f}{I^2}$$

With:	fusing integral	Θ_f	in A^2s
	operation time	t	in s

The temperature profile along the fuse element is constant. At constant current it rises somewhat faster than proportionately with time.

4_Temperature dependence of the fusing integral Θ_f

The fuse material parameter F and therefore the operation time t depends also on the temperature of the connecting wires T_3. This defines a cable temperature dependent derating factor f_T :

$$f_T = \frac{F}{F_0} = 1 - \frac{\ln\left[1+\alpha_\rho\left(T_3 - T_0\right)\right]}{\ln\left[1+\alpha_\rho\left(T_S - T_0\right)\right]} \approx \frac{T_S - T_3}{T_S - T_0}$$

with: fuse material temperature coefficient α_ρ in 1/K

fuse material parameter F in (A/mm²)²s

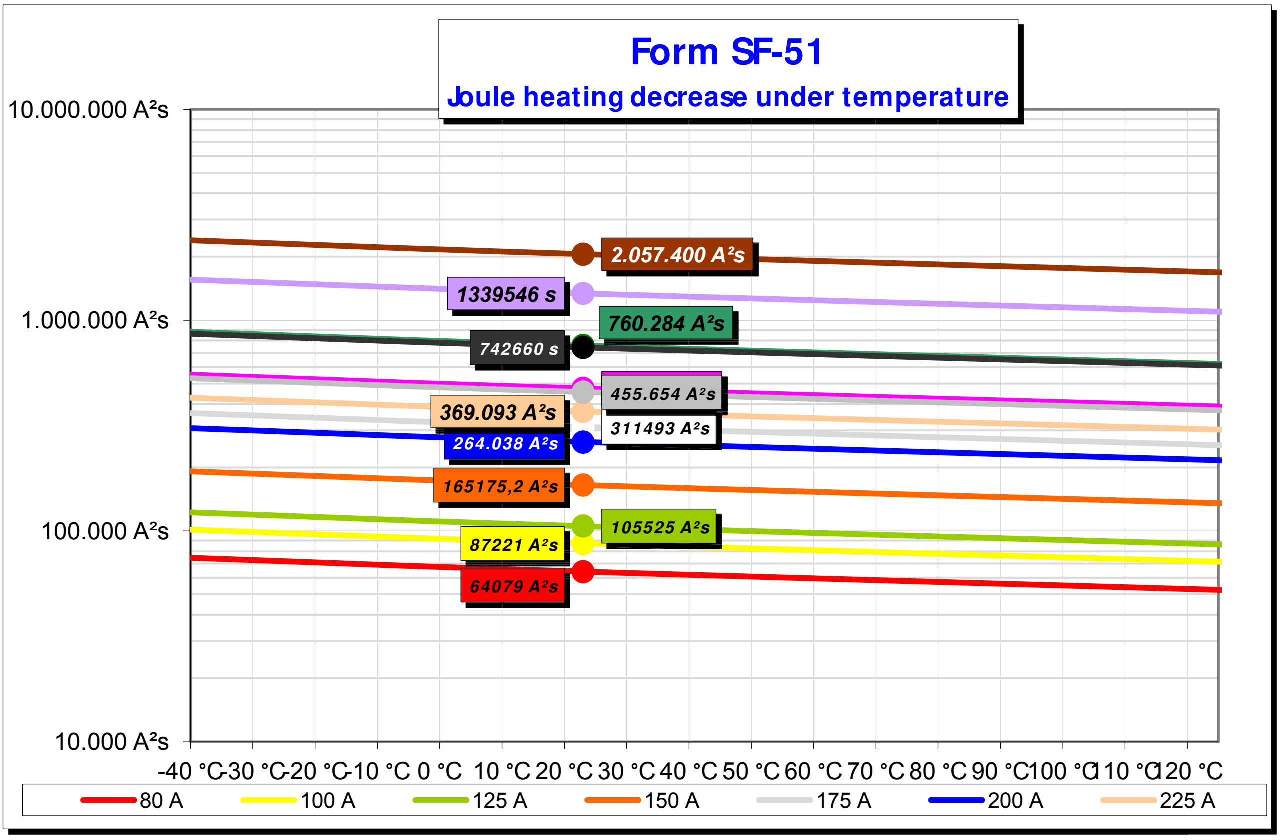
fuse material constant at 20 °C F_0 in (A/mm²)²s

reference temperature T_0 = 20 °C

connecting wire temperature T_3 in °C

fuse melting temperature T_S in °C

The following diagram shows the temperature dependence of the fusing integral Θ_f for the SF 51.



5_Connecting wire temperature
Under the assumption that the temperature difference from the fuse element to connecting wire can be neglected the connecting wire temperature is given by the effective wire current:

$$T_3 = a\, I_{eff} + b\, I_{eff}^2 + T_1$$

with:	linear cable parameter	a	in K/A
	square cable parameter	b	in K/A
	effective wire current	I_{eff}	in A
	ambient temperature	T_1	in °C

Connecting wire temperature T_3 *and characteristic parameters* a *and* b *can be calculated with the tool from Physical Software Solutions, Münsing, Germany.*

6_Effective connecting wire current
The effective wire current I_{eff} can be calculated with the impulse repetition time t_p

$$I_{eff} = \sqrt{\frac{\Theta}{t_p}}$$

with:	current time integral	Θ	in A²s
	impulse repetition time	t_p	in s
	effective wire current	I_{eff}	in A

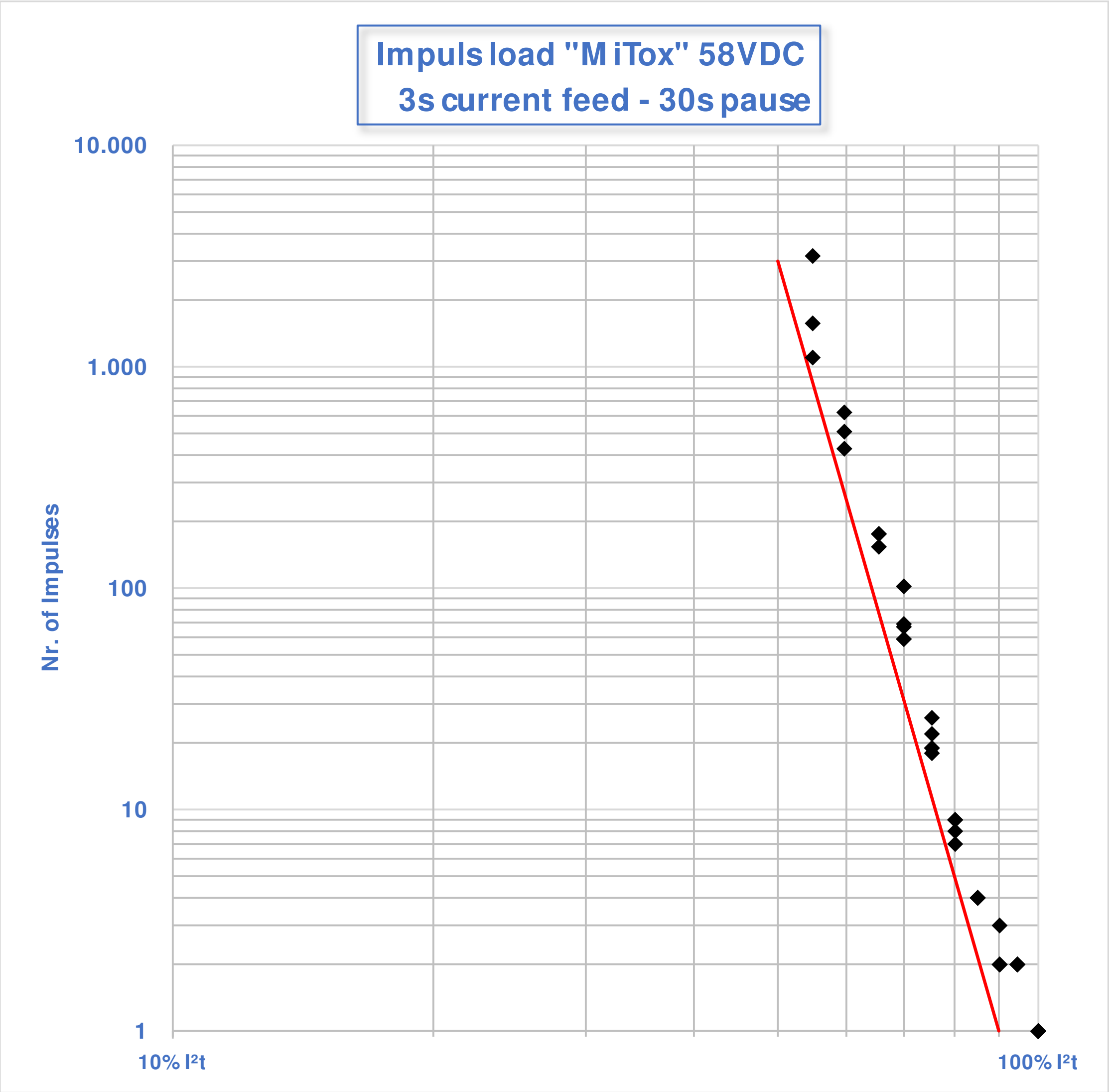
Impulse endurance
The application of short time impulses to a fuse seem to create some fatigue which is accumulated to a certain extent. This leads finally to an interruption of the fuse element after a number of impulses although the load of a single impulse is within its specification. The observed effect can be described with a derating factor f_n depending on the number n of impulse applied.

$$f_n = \frac{1}{\sqrt[m]{n}}$$

with:	derating factor	f_n
	number of impulses	n
	derating power	$m \approx 14$

Mid-time behaviour

The key value to characterize the mid-time behaviour of fuses is the heat transfer to the end connections. This leads to a sinus-profile of the temperature along the fuse element. The maximum is in the middle, provided both ends have the same temperature. At constant current temperature rises somewhat slower than proportionately with time and finally levels off towards a steady state.



Due to the sinus-shape of the temperature profile, there is a maximal permissible length of the fuse element. Sinus angle should be below 180°. At 180° the fuse disconnecting current reaches zero.

The border between short- and mid-time is characterized by the time constant of the fuse element, which can be calculated from the material constants and the length l of the fuse element:

$$\tau = \frac{\gamma}{\lambda}\left(\frac{l}{\pi}\right)^2$$

With:	specific heat capacity	γ	in W/(m K)
	heat conductivity	λ	in W/(m K)
	length of the fuse element	l	in m

Summary

The characteristics of fuses specified for constant load are not applicable for alternating load. Especially for high current peaks of short duration an adequate reduction of the impulse amplitude has to be applied. The necessary design rules were presented and given in relation to the fatigue probability.

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Literature

H.-D. Liess, M. Jakab: Berechnung von Schmelzsicherungen; internes Dokument, UniBwM 24.05.2015.

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