

Model-Based Circuit Protection Using Solid State Switches

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ABSTRACT

Currently, circuit breakers and, in most cases, thermal fuses are used for wire protection due to their low cost and robust design. As an alternative, solid state switches are being considered within future electrical distribution systems (EDS) for several reasons, e.g. resetability, diagnosis, smaller tolerances, and reduced dependencies on ambient temperature or arcing. Particularly if combined with benefits on the system level, such an application can be advantageous.

The new approach presented in this paper uses a thermal model of the wire instead of only an emulation of the thermal fuse behavior. This allows, based on the electrical current profile, the calculation of the wire temperature and thus a robust and precise protection of the wire. In addition, it minimizes the probability of faulty switching, which is of particular importance with regard to safety-critical electrical functions. Hence, results include higher reliability and a reduction of the wire cross-section area and copper usage. The paper describes the theory, the method and its requirements, and the basic algorithm, as well as initial simulation and measurement results.

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INTRODUCTION

The mandatory usage of fuses within the electrical distribution system (EDS) has a strong impact on both the reliability of the power supply and on the cross section of the connected wires, which determines the weight and required amount of material, especially of copper. Currently, circuit breakers and, in most cases, thermal fuses are used due to their low cost and robust design. However, for future EDS architectures, the implementation of fuses using solid state switches is being considered for several reasons, e.g. resetability, diagnosis, smaller tolerances, and reduced dependencies on ambient temperature, arcing, or pulse sequences. In addition, there can be advantages on the system level, especially for higher voltages or in combination with other switch-based functionalities such as pulse width modulation, power multiplexing, or substitution of relays.

Until now, smart solid state switches only emulate the behavior of thermal fuses and are therefore based on a fixed time versus current data set. The new approach presented in this paper, however, uses a thermal model of the wire and the electrical current profile to

calculate the wire temperature and thus allows a precise determination of a critical failure. As the primary function of a fuse is the protection of the wire, such virtual temperature monitoring provides the most direct and reliable information possible. This thus minimizes the probability of faulty switching and simultaneously assures an exact and robust detection of a critical current path, e.g. a short circuit. Results include higher reliability, a reduction of wire cross-section area, and decreased copper usage. Another advantage is that further improvements are possible if additional data about the wire, e.g. the ambient conditions or the wire location, can be made available.

The paper describes first the thermal modelling of a single wire followed by an experimental validation and a tolerance estimation. Based on this, the algorithm for the model-based circuit protection is derived and, as a reference, a data-driven model for the behavior of thermal fuses is given. Thus, simulations using stationary and dynamic current profiles allow comparative investigations. The results and their limitations are illustrated and discussed.

MODELLING OF A SINGLE WIRE

Theory

The thermal behavior of a single wire in air is considered to be the worst-case scenario. Hence it is chosen as the basis for the following modelling. Nevertheless, it should be mentioned that under certain conditions, the temperatures within wire bundles can be even more critical [1] and should also be considered.

Single wires have been subject to several studies, e.g. [2][3] and can be described with a straightforward approach using fundamental laws of physics. If p is the dissipated power per volume, T the temperature, and λ and c the specific thermal conductivity and capacity, one obtains:

$$p_c = p_{el} - p_{\lambda} \rightarrow c \frac{\partial T}{\partial t} = p_{el} + \lambda \left(\frac{\partial^2}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) \right) T \quad (1)$$

If the longitudinal heat transfer (in z-direction) is neglected, and a homogeneous temperature distribution within the conductor is assumed, one gets:

$$\frac{I^2 R'_{20} (1 - \beta(T_{20} - T_0))}{G_s - I^2 R'_{20} \beta} + T_0 = \frac{c_{con} q + c_{ins} \frac{\pi}{8} (d_{ins}^2 - d_{con}^2) \left(1 + \frac{G_s}{G_{\alpha}} \right) \frac{\partial T}{\partial t} + T}{G_s - I^2 R'_{20} \beta} \quad (2)$$

I : Current through the wire

R'_{20} : El. wire resistance per length at $T_{20} = 20^\circ\text{C}$

β : Thermal coefficient

T_0 : Ambient temperature

c_{con}, c_{ins} : Specific volumetric heat capacity of conductor and insulation

d_{con}, d_{ins} : Diameters of conductor and insulation

G : Heat conductance values

If only the relative temperatures with respect to the ambient temperature T_0 are considered, [equation \(2\)](#) can be written as:

$$\vartheta_t = \tau_t \frac{\partial \vartheta}{\partial t} + \vartheta, \quad \vartheta = T - T_0 \quad (3)$$

with:

$$\vartheta_t = \frac{I^2 R'_{20} (1 - \beta \vartheta_{20})}{G_s - I^2 R'_{20} \beta} \approx m_{\vartheta} I^2 \quad (4a)$$

$$\tau_t = \frac{c_{con} q + c_{pvc} \frac{\pi}{8} (d_{ins}^2 - d_{con}^2) \left(1 + \frac{G_s}{G_{\alpha}} \right)}{G_s - I^2 R'_{20} \beta} \quad (4b)$$

If λ_{ins} is the specific thermal conductivity of the insulator and α is the thermal transition coefficient between the insulation and air, which represents radiation and convection, the heat conductance values are given as

$$G_{ins} = \frac{2\pi\lambda_{ins}}{\ln \frac{d_{ins}}{d_{con}}}, \quad G_{\alpha} = \alpha\pi d_{ins}, \quad G_s = \frac{G_{\alpha} G_{ins}}{G_{ins} + G_{\alpha}} \quad (5)$$

The coefficient α depends on the wire diameter and temperature and can be described [4] as follows:

$$\alpha = \left(K_D \frac{1}{\sqrt{d_{ins}}} + K_T \sqrt[5]{\vartheta} \right)^2 \quad (6)$$

Validation

By applying a constant current to wires within a housing that minimizes air convection and measuring the temperature via the electrical resistance [2], one gets:

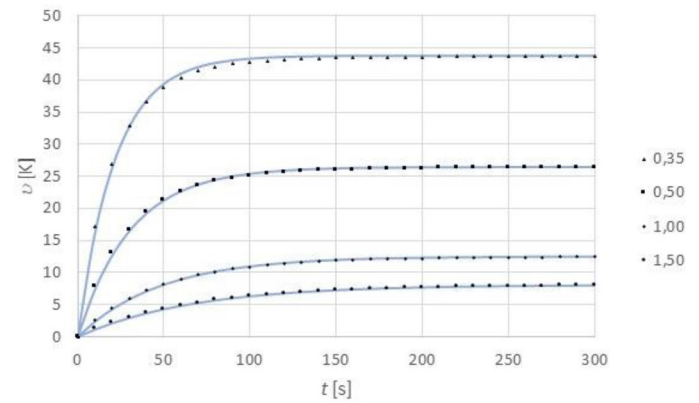


Figure 1. Temperature increase versus time at $I=10\text{A}$ for various cross-section areas [in mm^2]. Dots represent measured values and the lines are best fits

The best fits shown in [figure 1](#) were calculated with

$$\vartheta_{fit} = \vartheta_{fit\infty} \left(1 - e^{-\frac{t}{\tau_{fit}}} \right) \quad (7)$$

The comparison between the fit parameters ϑ_{fit} and τ_{fit} , and the calculated values ϑ_t and τ_t using [equations 4, 5, and 6](#), is depicted in the following [figures 2a and 2b](#), respectively.

The results show the expected linear relationship, however, the calculated values are 10% and 16% higher than the measured data. But, taking into consideration that the straightforward calculation is based on ideal wire data and theoretically derived values of K_D and K_T , and that the measurement is very sensitive to even marginal air flows, the small deviation is acceptable.

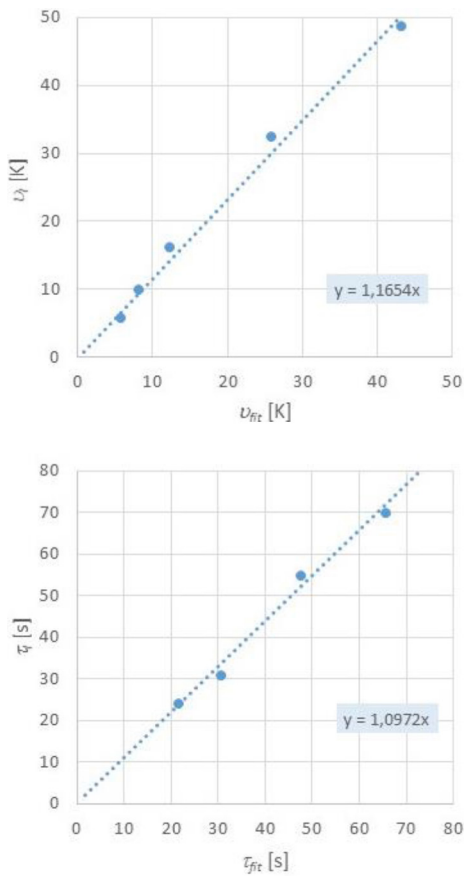


Figure 2. Comparison between fit parameters and calculated values a) (above) v_i versus v_{fit} , b) (below) τ_i versus τ_{fit}

Tolerances

For a model-based fusing concept it is mandatory to quantify the impact of tolerances (uncertainties) on wire (characteristics, parameters) such as conductor diameter d_{con} , insulator diameter d_{ins} , and electrical resistance R_{To} . For this purpose, equations 4, 5, and 6 allow a worst-case calculation by using the specified minimum, typical, and maximum data of the aforementioned quantities.

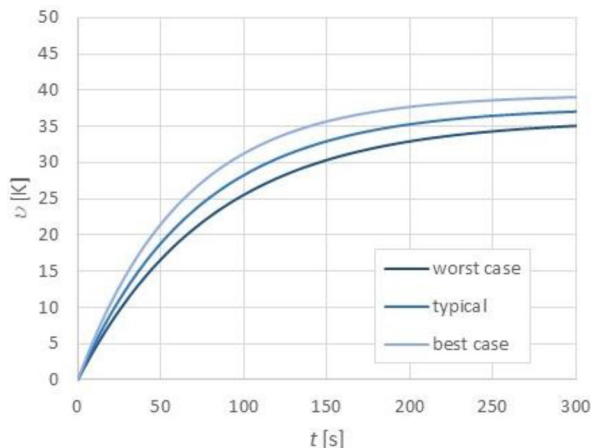


Figure 3. Tolerance analysis for $q=1.5 \text{ mm}^2$ wire (Cu) and $I=20\text{A}$: Temperature increase versus time

Table 1. Case analysis: Impact of wire tolerances

Case Analysis	best case	typical	worst case
	$m_{v,max}$ $\tau_{i,min}$	$m_{v,typ}$ $\tau_{i,typ}$	$m_{v,min}$ $\tau_{i,max}$
d_{wire}	min	typical	max
d_{con}	max	typical	min
R_{To}	min	typical	max

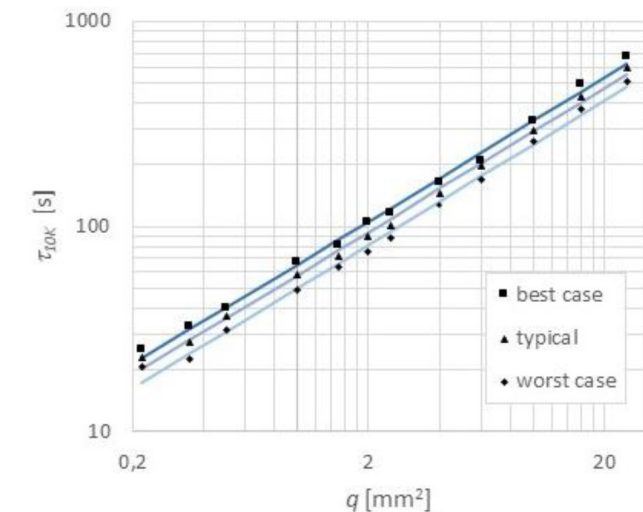
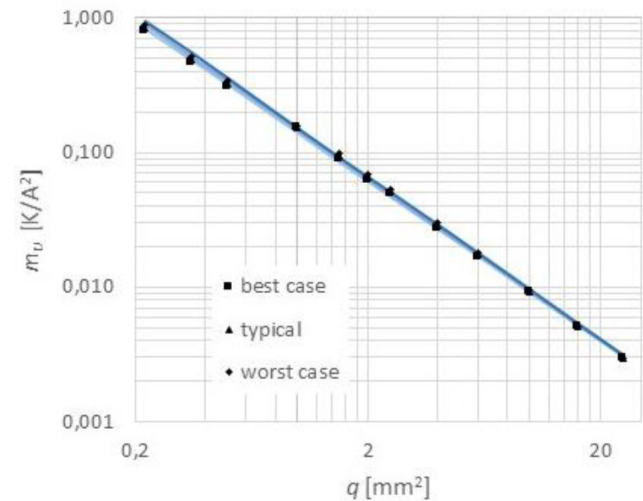


Figure 4. Tolerance analysis of τ_i and m_v for various cross sections

Figure 3 depicts as an example the temperature rise versus time for a $q=1.5 \text{ mm}^2$ (Cu) and $I=20\text{A}$ FLRY wire. As shown, the wire tolerances have a considerable impact on both the final temperature and the time constant. Hence, a model-based fusing concept must take into account the worst-case scenario. Finally, in figure 4, the results of the tolerance analysis for various cross-section areas is presented, where $m_v = v_i / I^2$ (see equation 4a). One can assume, that the deviations due to tolerances are in the range of $\pm 5\%$ for m_v and $\pm 15\%$ for τ_i .