A model-based automotive smart fuse approach considering environmental conditions and insulation aging for higher current load limits and short-term overload operations

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***Abstract*—This contribution presents a new concept for model-based automotive smart fuses, which takes indirectly into account the influence of real environmental conditions such as neighboring cables and local ambient temperatures. The proposed concept is based on a thermal cable model for the standard cable protection and additionally on the measurements at the cable ends and thus enables a short-time overload operation, which can be particularly important in safety-relevant driving situations. The reduction of lifetime of the cable caused by thermal overload is also monitored and used as an additional tripping criterion.**

***Keywords*—smart fuse, thermal modeling, automotive power supply system**

I. Introduction

Conventional melting fuses have been in use in automobiles for years to prevent thermal damage of cables due to their high reliability and low costs. However, the melting fuses always trip at melting temperature of fuse wire, regardless of the temperature of the cable to be protected. This might lead to over-dimensioned cable cross sections due to the significantly different thermal behavior of the fuses and cables and large safety margins in the standards, e.g. [1], [2]. By contrast, smart fuses planned for future power supply systems of vehicles should work on the principle that they estimate the cable temperature depending on a measured load current and break the circuit current with the help of a semiconductor or relay when a specified critical cable temperature is exceeded. Here, as with the melting fuses, the basic approach for smart fusing also requires worst-case assumptions such as single laying of air cooled cables at maximum possible local ambient temperature. Due to a better matching to the cable and a continuous current monitoring, the smart fuses generally make a cross-section reduction possible. In case they are implemented as a part of smart power distributors with powerful microcontrollers and communication interface, the smart fuses can offer even more potential, especially if an accurate estimation of cable temperature is available. Thus, the cable can be operated for example with a higher current if the cooling effect of real environmental conditions could be taken into account. A possible solution here is that the smart fuse monitors not only the current through the cable but also the voltage drop along the cable and calculate the cable temperature indirectly from the cable resistance. Since such an operation mode is only needed for higher currents, it is expected to achieve a sufficient accuracy in resistance measurement due to increasing voltage drop. The issue with a non-uniformly distributed resistance along the cable can be dealt by using a thermal cable model which is axially discretized and parameterized for the worst-case.

II. Thermal Modeling Of Automotive Cables

A thermal cable model to be implemented as smart fuse model running on low-cost microcontrollers requires some simplifying assumptions. Firstly, as a standard approach, a free air installation without any turbulent air flow around the cable will be assumed, so that the heat transfer between cable surface and surrounding air takes place only via the thermal radiation and natural convection. In this paper, thermal equivalent circuit models for cables will be used which are easily parameterizable via physical cable properties and easily extendable by connectors, additional conductors or insulation layers e.g. for high voltage shielded cables [3].

A. *Thermal Equivalent Circuit for Radial Heat Flow*

Assuming a long cable with length $l \gg d_i$ (d_i: outer diameter of insulation) and connections at both cable ends do not affect the temperature in the cable, the thermal behavior of the single core unshielded cable can be modelled via a simple thermal equivalent circuit with lumped elements as shown in Fig. 1. The model describes only the radial heat flow from the conductor up to the cable surface to surrounding air environment, which means the cable length has no impact on the thermal behavior. In this case per unit length (p.u.l.) parameters can be formulated with an apostrophe (′) character.

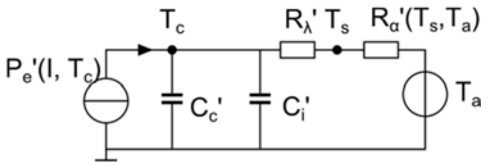


Fig. 1. The thermal circuit model of single core unshielded cables for radial heat flow

In Fig. 1 the heat source P_e' represents the power loss p.u.l., P_e'=P_e/l and is calculated by $I^2 \cdot R_c'(T_c)$ via the electrical current I and the temperature dependent p.u.l. conductor resistance R_c' which is given in equation 1. Here, T_c is the conductor temperature, R_0' is the electrical conductor resistance per meter at the temperature T_0 (e.g. 20 ° C) and α_T is the linear temperature coefficient of the conductor material (e.g. 3,93e-3 [1/K] for copper).

$$R_c' = R_0'\big(1 + \alpha_T(T_c - T_0)\big) \tag{1}$$

The calculation of the thermal capacitances for the conductor (C_c') or insulation (C_i') takes place for both on the basis of specific heat capacity per cross sectional area (c_c' and c_i'), where r_i and r_c are the radius of the conductor and of the insulation.

$$C_c' = c_c'\pi r_c^2 \tag{2}$$

$$C_i' = c_i'\pi(r_i^2 - r_c^2) \tag{3}$$

Compared to the insulation the thermal resistance of the conductor is extremely small and can therefore be neglected. Thus, only the thermal resistance of the insulation itself and between the insulation and the surrounding air are significant as given in equation 4 and 5. Here, R_λ' considers the heat conduction through the insulation layer, where λ is the thermal conductivity of the insulation, and R_α' takes into account the heat dissipation to the environment through the natural convection and the radiation.

$$R_\lambda' = \frac{ln(r_i/r_c)}{2\pi\lambda} \tag{4}$$

$$R_\alpha' = \frac{1}{(\alpha_c+\alpha_r)2\pi r_i} \tag{5}$$

In equation 5, the parameter α_r is the radiative heat transfer coefficient and calculated using the emission coefficient of the cable surface ε (typically 0,95), the Stefan-Boltzmann constant σ, the absolute ambient temperature T_a and surface temperature T_s as follows:

$$\alpha_r = \frac{\varepsilon\sigma\left({T_s}^4 - {T_a}^4\right)}{T_s - T_a} \tag{6}$$

In contrast to the radiation, the calculation of the convective heat transfer coefficient α_c is more difficult because of the complex nature of the convection. Here, a common approach is the similarity solution for an infinite horizontal cylinder which can be expressed by equation 7, where Nu is the Nusselt number and λ_{air} is thermal conductivity of air.

$$\alpha_c = \frac{Nu \cdot \lambda_{air}}{\pi r_i} \tag{7}$$

It must be noted that Nu and λ_{air} are both depending on the surface and also the surrounding air temperature. For the models in this paper the Nusselt number and all needed physical air constants are calculated according to [5], [6].

B. *Thermal Equivalent Circuit for Longitudinal Heat Flow*

To take into account the impact of the contacts on the temperature maxima in the cable an extended, axially discretized thermal equivalent circuit, as shown in Fig. 2, can be used. This model consists of several cable segments where each segment is represented by a thermal equivalent circuit as shown in Fig. 1 (a) considering corresponding segment length l_{seg}. The heat flow between adjoining segments takes place via thermal resistances between the corresponding heat sources. Thus, each segment has a thermal resistance on both sides, respectively, which is calculated depending on the corresponding segment length $l_{seg,n}$ as follows:

$$R_{ax,n} = \frac{l_{seg,n}/2}{\lambda \pi {r_c}^2} \tag{8}$$

As depicted in Fig. 2 the cable is terminated at both ends with a temperature source, which considers the boundary condition. This approach is valid as long as the electric power loss through the contacts does not affect the cable temperature significantly. Otherwise, the sources must be replaced by appropriate thermal contact models.

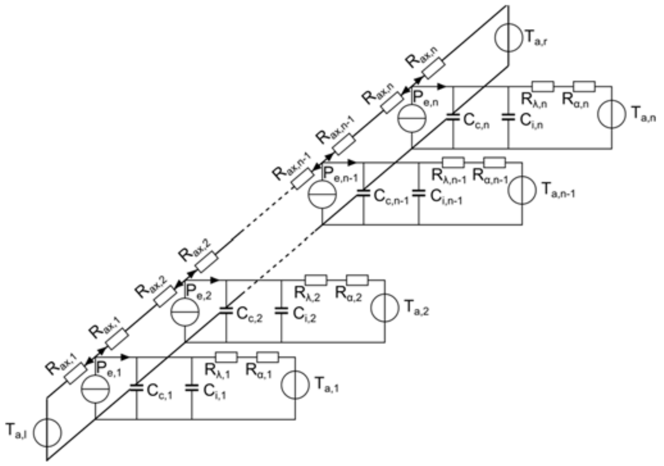


Fig. 2. The circuit model of single core unshielded cables for both radial and longitudinal heat flow

Different ambient temperature zones along the cable can be taken into account via the ambient temperature source of each individual segment, whereby the initial temperatures of the thermal capacitances must be first calculated for stationary case.

C. *Bundle Installation*

Due to a typical bundle installation, the thermal behavior of a cable can change significantly. The convection and radiation will take place at the bundle surface and the cable can be can be cooled or heated by neighboring cables or other adjoining surfaces. However, in most cases a reduction of the cable temperature can be expected due to strict rules in development of vehicle power nets. In this paper, the bundle installation will be considered by extending the presented thermal models, as shown in Fig. 3. Here it is assumed that none of the neighboring cables is loaded, thus the heat conduction between the cable to be modeled and the bundle surface takes place via only an additional RC thermal network. Furthermore, a uniform bundle cross-section along the entire cable is assumed and the radiation and convection are considered by increasing the cable diameter. The parameters for the RC-network can be found with the help of a FEM-simulation.

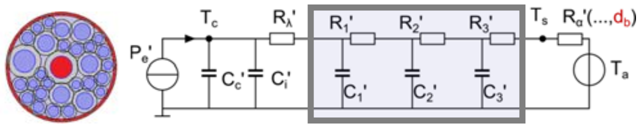


Fig. 3. Simplyflied modeling approach of bundle installation for a cable

In order to consider a sample bundle installation with a diameter of ca. 10 cm the following values will be used, which are given per unit cable length, respectively.

- R_1': 2,2, R_2': 0.05, R_3': 0,94 $[K/W \cdot m]$
- C_1': 0.31, C_2': 629, C_3': 1259 $[J/K/m]$

This configuration shall only be needed to consider a typical temperature profile of a bundle installation in the simulation and is not included in smart fuse model.

III. INDIRECT TEMPERATURE MEASUREMENT

Using the temperature dependency of the cable resistance (see equation 1) it is possible to find the cable temperature with only voltage drop and current measurements. However, as the resistance distribution along the cable can typically have a non-uniform distribution due to non-uniform heating, the measured resistance must be corrected in order to find the temperature maxima along the cable, which is primarily dependent on the local ambient and contact temperatures.

A. *Correction Factor for Resistance Measurement*

The correction factor needed for resistance measurement is described in Fig. 4 (a) by the comparison of the distributed resistance with the measurable resistance for a 1 m, 10 mm^2 cable (PVC, copper) in case of an ambient and contact temperature of 25 °C and a constant load current of 100 A. As can be seen here, the measured resistance (red) must be multiplied with a correction factor k in order to find the maximum resistance and temperature in the middle of cable.

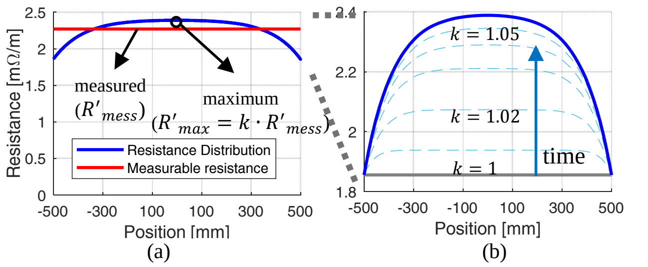


Fig. 4. Correction factor for the cable resistance measured between cable contacts (a) and its time dependency (b)

Fig. 4 (b) shows the change of k over time, where a maximum value of 1,05 (5 %) results for stationary case. Fig. 5 shows the influence of the different ambient temperature zones (a) on the resistance (b) for the same cable with the same load current for the stationary case. In Fig. 5 (b) the correction factors k are also given in the figure legends. First, it is assumed that the cable has a local temperature zone with 85°C in a section of about 1/3 of cable length and otherwise 25 °C. In this case, the temperature distribution no. 4 (red line) leads to the worst-case for the correction factor, 1,125. Only shifting the temperature zone and using a contact temperature of 85 ° C (blue line) leads to a maximum deviation of k by about 2 % compared to this worst-case, which would cause only 5 – 7 K deviation in the indirect measured temperature using the equation 1 with an α_T for copper.

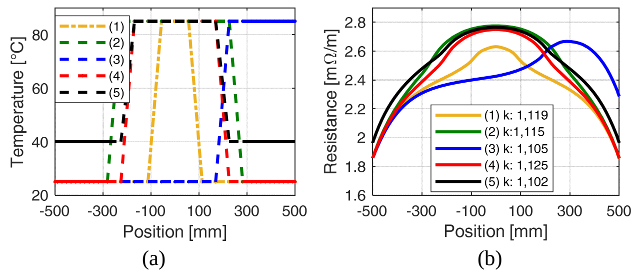


Fig. 5. Distribution of electrical resistance (b) (stationary case) for different ambient temperature zones (b)

By assuming that different ambient temperature zones may impact the distribution of the cable resistance, in a bundle in the same way as a single cable, the correction factor can be calculated using the thermal model parameterized by worst-case ambient and contact temperatures (see section II.B).

B. *Required Measurement Accuracy*

Since in overload situations the load current is large, it is possible to measure the resulting voltage drop with higher accuracy as with normal operating currents. Fig. 6 (a) gives the temperature resolutions versus the load currents with a voltage resolution of 1 mV, 5 mV and 10 mV for a 1 m, 10 mm^2 copper cable. Here, an accuracy of ± 10 % of current measurement is also highlighted by colored areas for each voltage resolution. Due to the linear relationship between the change of conductor resistance (ΔR) and conductor temperature (ΔT), a simple scaling of the temperature resolution for other cross sections or cable lengths is possible. For example, the measurement resolution will be doubled by the doubling of the cable length, the load current or by the halving the cross section. In Fig. 6 (b), the damage characteristic for this cable is shown in the case of PVC insulation for an ambient temperature of 25 °C (yellow) or 85 °C (red), where the minimum long-term damage current is 100 A for an ambient temperature 25 °C and 130 A for 85 °C. At these higher currents, a temperature resolution of less than 2 K under a voltage resolution of 1 mV is achievable. At 5 mV, an acceptable temperature resolution of ca. 7 K is still possible, which would halve for a cable length of 2 m or for a cross section of 4 mm^2.

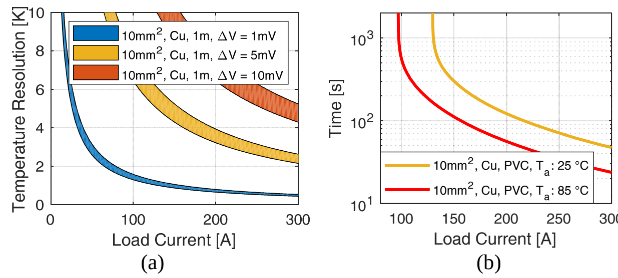


Fig. 6. Temperature resolution vs. load current at different voltage measurement accuracies (a) and damage characteristic (b) for a single 10 mm^2 PVC air cooled cable

IV. SMART FUSE MODEL

Fig. 7 shows schematically a possible structure of a smart fuse controller which can be derived from the analyses already made in the previous sections. It bases on temperature calculations made with a thermal cable model (a) and with the help of the indirect resistance measurement (b). It is assumed that a sufficiently accurate measurement of the voltage drop (ΔU) and current (I) through the cable is available.

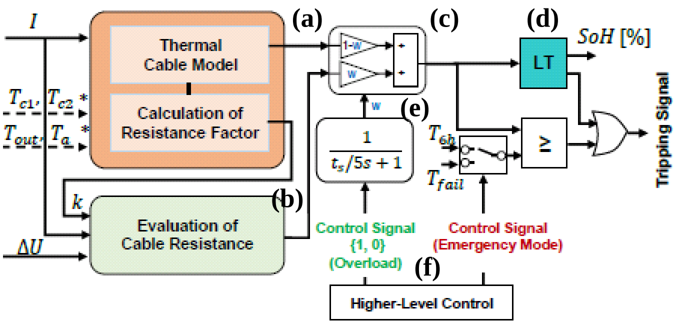


Fig. 7. Schematic structure of proposed smart fuse model (* optional)

In default operating mode the smart fuse produces a tripping signal based only on the thermal model (a) considering predefined worst-case conditions in order to protect the cable from critical temperatures according to standards. In a second operating mode, the available load reserve of the cable can be better exploited through the estimation of the cable temperature via the measured cable resistance (b), where the correction factor k is provided by the thermal worst-case model (a). A continuous transition between the two operating modes can be achieved by a low-pass filtering (e) on the control signal, where the switching time is set via the parameter t_s. This is also needed if the load current decreases intermittently during overloading, which could temporarily lead to switch to the default operation mode (a) due to inaccurate measurement. The aging of the cable insulation can also be used as an additional tripping criterion by continuous monitoring of the cable life time (d) (see the next section). This function is especially necessary in emergency situations that may require temporary overloading of the cable. Switching to this operation mode may be initiated by a higher-level power network diagnosis.

A. Tripping Conditions

In contrast to the melting fuses, the tripping condition for smart fuses can be defined nearly arbitrarily. Since in the standards the permissible temperatures of typical insulation materials are already specified for given lifetime periods, these can be used as tripping criterion for smart fuses. For example, according to various standards, a PVC cable has a lifetime of 3000 hours in case it is continuously operated at 105 °C (T_{3000h}, long-term aging), whereas its lifetime will only last for 6 hours at 155 °C (T_{6h}, thermal overload). In most tripping cases, it is expected that the current is very high, such as in a short-circuit situation, and thus the tripping time should follow instantaneously. Therefore, it is reasonable to use the thermal overload temperature T_{6h} as the main tripping criterion of smart fuses. However, in contrast to the melting fuses, which are typically fast-acting, especially at higher currents, compared with cables to be protected, smart fuses will track the cable temperature and trip with a similar time constant as the cable. Therefore, the smart fuse must consider the cable aging as an additional tripping condition. For the spent lifetime of a cable a modified Arrhenius-Equation can be used, as shown in equation 9, where A and b are insulation material-dependent constants, k is the aging speed e.g. in $[1/h]$ and T is the temperature in Kelvin [7].

$$k = Ae^{\left(-\frac{b}{T}\right)} \tag{9}$$

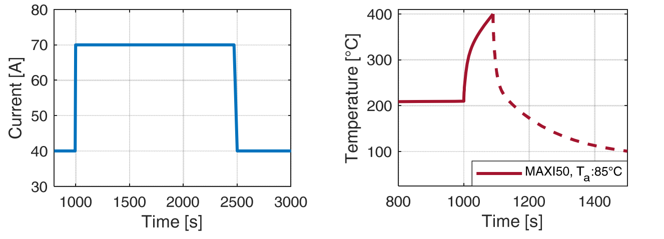
If assumed that the aging process of the cable insulation under a given constant temperature is linear, the spent lifetime can be calculated for any temperature profile by integration over the aging speed according to equation 10.

$$LT_{spent} = \int Ae^{\left(-\frac{b}{T(t)}\right)}dt \tag{10}$$

As already shown in Fig. 7 (d) the smart fuse monitors the used life time permanently and can also output the remaining life time as “State of Health” (SoH) of the cable in percent via $100 \cdot (1 - LT_{used})$.

B. Application Example

The proposed smart fuse approach shall be presented in the following with the help of a simulation example. The chosen setup consists of a safety-relevant electric device with a constant load current of 40 A, a melting fuse (MAXI50) and a 1 m PVC copper cable with 6 mm² cross-section, complying the dimensioning rules in the automotive standard VW-60306. The consumer shall be located in the engine compartment so that a local ambient temperature up to 85 °C and a contact temperature up to 40 °C for both cable ends are possible. It is assumed that the consumer has been operated first with a constant current of 40 A and suddenly a malfunction requires a short-time overload current of 70 A. The current profile (a) and the resulting temperature response of the melting fuse (b) for the simulation is shown in Fig. 8. As can be seen here, the melting fuse will trip ca. 90 s after the current is increased from 40 A to 70 A (model for melting fuse according to [8]).



(a) (b)

Fig. 8. Current profile (left) and the resulting temperature profile (right) for a MAXI50 fuse (tripping at 1090 s)

Now it is assumed that the cable's environmental conditions are much better than the worst-case assumptions for cross-section dimensioning. This is considered in the simulation with the help of the extended thermal model as given in section II.C. The real ambient temperature shall be 60 °C and the real contact temperature for both end is 40 °C, which are unknown to the smart fuse. Thus, the smart fuse must consider in normal operation mode an ambient temperature of 85 °C. The real temperature curve from simulation for the given configuration is shown with a black curve in Fig. 9.

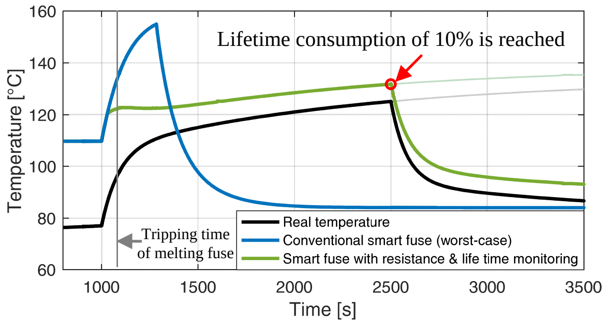


Fig. 9. Comparison of the real temperature profile (black) with temperature profiles calculated by the smart fuse (blue: worst-case thermal model, green: worst-case thermal model combined with resistance measurement)

The resulting temperature profile for the smart fuse in the standard worst-case operation mode is given with the blue curve in Fig. 9. Here, the conventional smart fuse is able to last ca. 200 s longer as the melting fuse does, although the cable has still load reserves in reality (black). In Fig. 9, the green curve represents the temperature profile in case of a smart fuse with resistance measurement, which has been activated ca. 30 s after the overload has started. Here, the smart fuse uses an ambient temperature of 85 °C as worst-case and a contact temperature of 25 °C for both contacts to calculate a worst-case correction factor (see section III.A). In this case, the smart fuse offers ca. 20 minutes more operation time while overloading. The critical cable temperature 155 °C is not reached and the tripping takes place due to using up a lifetime of ca. 10 %.

V. Summary

In this work, a new concept for smart fuses has been presented. The proposed smart fuse model is based on a thermal cable model, which, in normal operation mode, can estimate the cable temperature under worst-case parameterization. The smart fuse model offers an additional operation mode for overloading currents, if an accurate measurement of the cable voltage drop is available. In this case the smart fuse evaluates the measured resistance with the help of the used thermal cable model. Thus, the real ambient temperature and the cooling effect of real lying situation (e.g. bundle installation) can be considered indirectly. Since the cable to be protected can be loaded up to the temperature limits by this approach, the model takes into account as a second trigger criterion the aging of the cable insulation, which is approximately calculated over time on the basis of Arrhenius equation.

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