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Influence of Electronic and Melting Fuses on the Transient Behavior of Automotive Power Supply Systems

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***Abstract*—In future automotive power supply systems, electronic fuses (eFuses) will be increasingly used for wire protection and controlling the power flow. However, the impact of eFuses on the overall power supply system is not well analyzed until now. Automated driving requires a stable power supply that should be robust against transient voltage and current pulses caused by, e.g., short circuit faults and subsequent fuse tripping. To remain fail-operational, such pulses must not affect other redundant components. In this paper, new behavioral simulation models for typical automotive melting and electronic fuses are presented that are optimized for the transient analysis of the fuse tripping event. The models are validated and parameterized by measurements. By simulating different supply topologies, the propagation of voltage and current pulses caused by a tripping event, and their impact on the system stability are analyzed. Key findings are validated by measurements. On the one hand, it is shown, that eFuses generate less critical overvoltages compared to melting fuses. On the other hand, the high current pulses caused by eFuse switching can trigger other eFuses in other remote branches to trip. With melting fuses, this behavior is not seen. Possible remedies for such a chain reaction are discussed.**

***Index Terms*—Automotive power supply, eFuse, melting fuse, simulation, transients.**

I. INTRODUCTION

AUTOMATED driving will increase the requirements for the safety of vehicle power supply systems [1]. The overall system shall be fail-operational to ensure safe operation even in the case of a single fault. This can be achieved by redundant systems, increased diagnostics, and the ability to react fast to faults and separate faulty parts of the supply system, if needed. These requirements cannot be met with conventional melting fuses and necessitate more sophisticated concepts like electronic fuses based on power semiconductors (eFuses) [2–5]. Beyond repeated switching capabilities, they can be easily enhanced to offer, e.g., voltage and current measurements. Intelligent wire protection algorithms can be realized, that extend the ampacity of wires and enable cross-section reduction [6, 7]. Because of these reasons, eFuses were also introduced in, e.g., industrial applications and aircrafts [8–10].

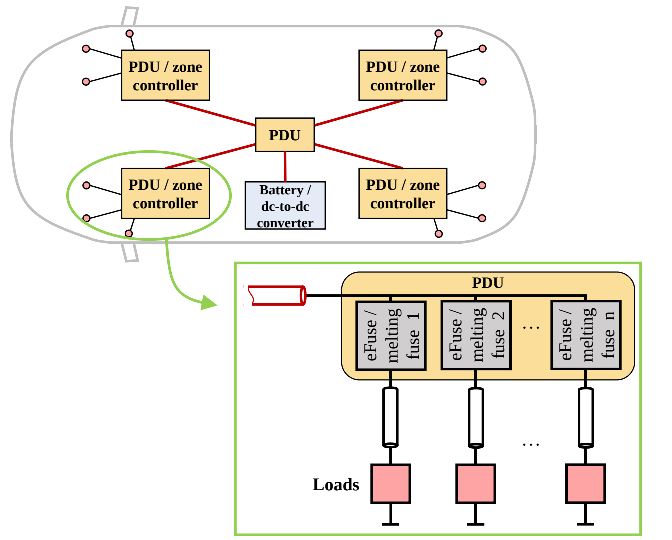

Fig. 1. Exemplary low voltage zonal power supply system with five **p**ower **d**istribution **u**nits (**PDU**s)

Despite the increasing usage of eFuses, the fast switching, which can cause high transients in supply systems, is not well investigated. Especially in the context of new supply systems for zonal architectures with higher currents [11], as exemplary shown in Fig. 1, additional research is required.

Component test series have been standardized to detect vulnerabilities in electronic systems against typical pulses. The most important ones are ISO 16750 [12] and the ISO 7637 [13] series. The standards are based on old vehicle architectures, generally without power electronic devices. More recently performed investigations, e.g. [14] or [15], criticize an inaccurate understanding of the switching arcs in the ISO standards. Most research on power supply system stability does not include fast switching events [16–19]. New developments like eFuses or zonal architectures are not considered at all in these works. Voltage transients of tripping melting fuses within spacecraft supply systems have been investigated in [20]. The switching behavior of eFuses in dc supply systems have been analyzed in [9] and [21], however, pulse propagation and the impact on other system components have been ignored. The propagation of voltage transients from an eFuse tripping event

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has first been investigated in [22], however, current pulses and critical interactions between multiple eFuses are not considered.

In this contribution, the impact of eFuses on the generation of transients in modern vehicle power supply systems is analyzed and compared to melting fuses. Different supply subsystems are investigated, mainly with the help of simulation. More accurate simulation models are developed and validated by measurements in laboratory setups. Validation results are shown. The current pulse propagation in larger supply networks and critical interactions between multiple eFuses are discussed for the first time.

The paper is structured as follows. In section II, the used methods are described, and the two investigated low voltage supply system networks are introduced. A significantly improved version of the melting fuse model from [22] is presented in section III. Furthermore, a universal eFuse model is described. With the validated models, both fuse types are then compared in the exemplary power supply systems. The impact of fuse switching on the load voltage stability is analyzed in section IV. Section V discusses possible influences on the operation of other eFuses. Key findings are confirmed by measurements. The results are discussed under practical aspects in section VI. Finally, section VII summarizes the most important results.

II. Analysis Methods and Analyzed Power Networks

In this section, the methods used in this contribution are briefly described. First, the basic simulation models are discussed. Then, the analyzed power supply systems are introduced and the measurement setup is described.

A. Simulation

The main findings of this contribution are based on simulations with models validated by measurements. For the basic supply system components, like sources, loads, and wires, models from [23] are used. Wires are modeled as RL circuits with the copper resistance and a simple inductance estimation of 1 µH per meter wire length [24]. For the fast transient analysis a simple battery model, consisting of a voltage source and a constant internal resistance, has been chosen. As loads, parallel RC circuits are used to model the behavior of **e**lectronic **c**ontrol **u**nits (**ECU**s) [18]; during the short investigated time intervals of pulse propagation, a static power consumption is assumed that is represented by the resistor. The capacitor stabilizes the ECU's supply voltage. The developed fuse models are described in detail in section III. All simulations are performed in MATLAB/Simscape.

B. Analyzed Supply Networks

For the following investigations, two different low voltage supply networks are considered. The first system, system I, is depicted in Fig. 2. It is a reduced subsystem consisting of a PDU with a 14 V battery supply, i.e., the lead-acid battery is fully charged, and two loads that are protected by fuses. The battery is connected through a 35 mm² copper wire of 4.5 m length. Load 1 and 2 represent a static 98 W energy consumer. For both loads, a

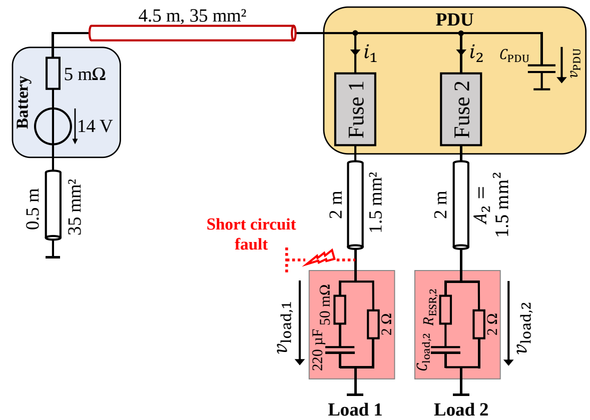

Fig. 2. Power supply system I (reduced system with only two loads)

Table 1:
Fuse Parameterization of Supply System I

	Parameter	Fuse 1	Fuse 2
eFuses	I_{nom}	20 A	20 A
	I_{OCP}	150 A	150 A
Melting fuses	I_{rated}	20 A	20 A

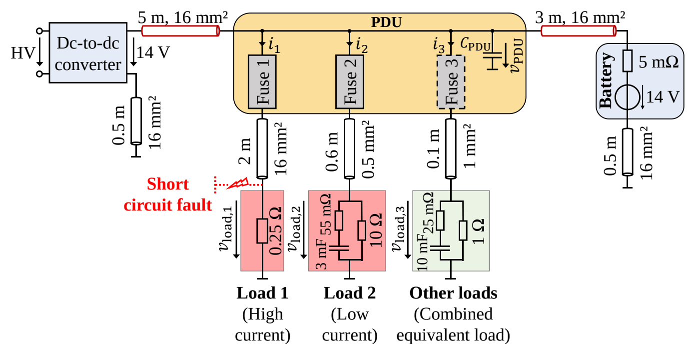

Fig. 3. Power supply system II (complex subsystem for higher reliability)

Table 2:
Fuse Parameterization of Supply System II

	Parameter	Fuse 1	Fuse 2
eFuses	I_{nom}	80 A	2 A
	I_{OCP}	400 A	20 A
Melting fuses	I_{rated}	100 A	3 A

capacitor with $C_{load} = 220\ \mu F$ and $R_{ESR} = 50\ m\Omega$ is assumed.

Two fuse configurations are considered: either melting fuses or eFuses. A stabilizing capacitance C_{PDU} inside the PDU is considered only for eFuses; the conventional melting fuse PDU has no capacitor. The melting fuses 1 and 2 are chosen according to the ampacity of the connected wires based on established design rules [25]. eFuses with a comparable nominal current were chosen, as no established rules exist. The parameters are depicted in Table 1. C_{PDU} is chosen to 100 µF.

System II is a more complex system with more loads and a redundant supply. It is depicted in Fig. 3. Load 1 is a high current

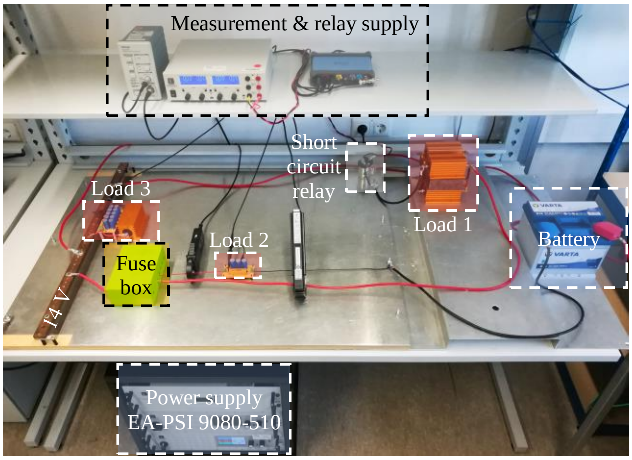

Fig. 4. Photograph of laboratory setup

load with a resistance of 0.25 Ω, i.e., 784 W. Load 2 is a low current load and assumed to be safety-relevant. It consumes 19.6 W. Load 3 represents additional components supplied by the PDU. As these components are all in parallel, a large capacitance of 10 mF and a short wire length of 0.1 m is chosen for the combined equivalent load. Load 3 affects the dynamic behavior of the system but is not analyzed further. The PDU is assumed to be supplied by a 2.1 kW dc-to-dc converter and a fully charged battery. Fuse 1 is chosen according to the wire ampacity and fuse 2 is chosen according to the connected load. Fuse parameters are depicted in TABLE 2. Again, configurations with electronic and melting fuses are considered. Only in case of eFuses, the PDU capacitance is chosen to $C_{\mathrm{PDU}} = 1$ mF. For melting fuses, this capacitance is zero. The branch connected to fuse 3 represents only uncritical consumers. As the fuse is assumed to always stay in conducting mode, a large melting fuse has been used that is not analyzed further.

The investigated fault scenario in both systems is a short circuit of load 1, which is considered as the most critical fault in these configurations because of the expected large fault current. The transient impact of this fault on the systems is analyzed.

C. Measurement

Measurements are performed to parameterize and validate the fuse models, and to confirm key findings of the following investigations. The respective networks are realized in a laboratory setup using ATO [26] melting fuses, eFuses, and a 12 V lead-acid battery with 44 Ah. RC loads are used to emulate the input behavior of an ECU [18]. Additionally, a laboratory supply (EA-PSI 9080-510) is used to approximate the behavior of a dc-to-dc converter (the supply is set to 14 V and the current limit is set to 150 A). A high-current relay initiates a short circuit fault. The transient voltage and current pulses of the fault and the subsequent fuse switching are recorded using a PicoScope 4824 oscilloscope.

A photograph of the realized laboratory setup supply system II can be seen in Fig. 4.

III. Fuse Models

This section presents the developed melting and electronic fuse models.

A. Melting Fuse Model

A new behavioral melting fuse model has been developed and is described in this section. Exemplarily, parameterization and validation are presented.

1) Overview: A melting fuse in its conducting state is simply a thin wire with a temperature-dependent resistance. When the fuse current exceeds the rated current I_{rated}, the wire temperature reaches its melting temperature (typically 400 °C [7]) after some time. During melting, an arc is first initiated that bridges the melting wire, and the current continues to flow. The arc resistance increases with the length of the melted wire. The resistance increases and the current decreases until the arc cannot be sustained anymore and expires. The circuit is open and the current drops to zero [27].

2) Modeling: As arc physics can lead to very complex models, a behavioral circuit model, as depicted in Fig. 5, has been developed. Major parts for arc modelling are taken from [28].

For the conducting behavior, the temperature of the fuse is modeled by a thermal RC network (refer to Fig. 6), as described and parameterized in [29]. Based on the resulting temperature, the wire resistance is typically modeled by a polynomial. At higher temperatures the resistance increases sharply with rising temperature. Measurements have shown that an exponential extension to a second order polynomial reflects the overall temperature behavior well:

$$R_{\mathrm{fuse}}(T) = R_{\mathrm{cold}}(1 + \alpha\Delta T + \beta\Delta T^2 + Ae^{B\Delta T}) \quad (1)$$

R_{cold} is the wire resistance at 25 °C and α, β, A and B are the temperature coefficients that need to be determined for each fuse type. All thermal parameters for a 10 A ATO fuse [26] are exemplarily given in Table 3.

The arc, initiated by the melting of the fuse, leads to a quickly decreasing current. To model the behavior of this complex process, [28] proposes an RC circuit that is switched in series with R_{fuse} once the melting temperature is reached at time t_{melt}. R_{arc} and C_{arc} depend on the operating point, specifically the melting current I_{melt} of the fuse at t_{melt}. Measurements with the fuse connected directly to a high current laboratory voltage source (EA-PSI 9080-510) and different supply wire lengths and cross sections have been performed to determine the R- and C-values. By fitting the simulated current and voltage curves to the measured ones, $C_{\mathrm{arc}}(I_{\mathrm{melt}})$ and $R_{\mathrm{arc}}(I_{\mathrm{melt}})$ could be found. For a 10 A ATO fuse [26], the parameters are exemplarily shown in Fig. 7. Equations (2) and (3) give approximating functions to the determined parameters. Outside the measured parameter range, the functions are not validated and should not be used.

After the arc is extinguished, the fuse is just an open circuit, modeled by an additional switch that is opened when the current reaches 0 A.

3) Validation: The melting fuse model has been validated with the test bench depicted in Fig. 8. The fuse branch can be

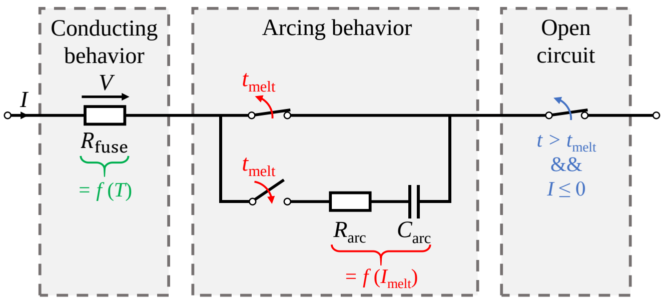

Fig. 5. Model of the electric behavior of an automotive melting fuse

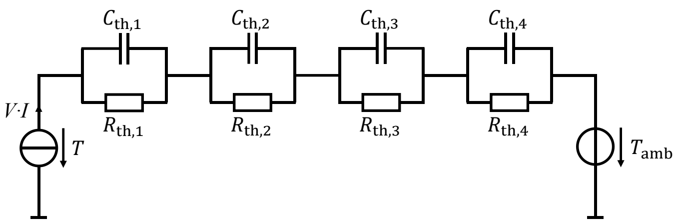

Fig. 6. Thermal network of melting fuse model

TABLE 3:
THERMAL PARAMETERS OF ATO 10 A MELTING FUSE MODEL

Parameter	$R_{th,1}$	$R_{th,2}$	$R_{th,3}$	$R_{th,4}$
Value	35.4 K/W	74.7 K/W	20.3 K/W	9.84 K/W

$C_{th,1}$	$C_{th,2}$	$C_{th,3}$	$C_{th,4}$	R_{cold}
74.4 mJ/K	4.16 mJ/K	0.905 J/K	16.9 J/K	7.68 mΩ

α	β	A	B
$3.61 \cdot 10^{-3}\,\mathrm{K}^{-1}$	$18 \cdot 10^{-6}\,\mathrm{K}^{-2}$	$1.75 \cdot 10^{-32}$	$0.2\,\mathrm{K}^{-1}$

$$C_{arc}(I_{melt}) = \begin{cases} e^{\frac{I_{melt}}{35}} - 1, & I_{melt} \leq 125\,\mathrm{A} \\ 1.38 \cdot I_{melt} - 137.9, & I_{melt} > 125\,\mathrm{A} \end{cases} \quad (\text{in } \mu\mathrm{F}) \tag{2}$$

$$R_{arc}(I_{melt}) = \begin{cases} -4.15 \cdot 10^{-3} \cdot I_{melt} + 1.1, & I_{melt} \leq 210\,\mathrm{A} \\ -0.65 \cdot 10^{-3} \cdot I_{melt} + 0.37, & 210\,\mathrm{A} < I_{melt} \leq 570\,\mathrm{A} \\ 0, & I_{melt} > 570\,\mathrm{A} \end{cases} \quad (\text{in } \Omega) \tag{3}$$

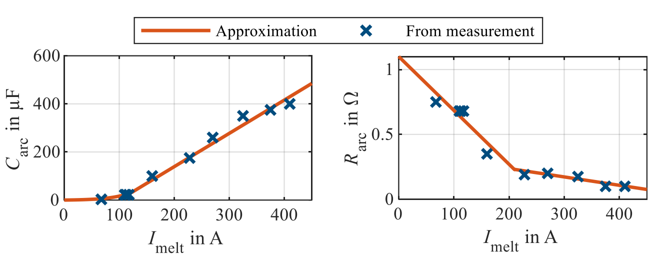

Fig. 7. Arcing circuit parameters of a 10 A ATO fuse for different melting currents

shorted to ground by the relay. A very low power (0.196 W, e.g., a system in idle mode) load (red box) is connected in parallel to the fuse branch. The 14 V voltage source is realized by a laboratory power supply with a sufficiently high maximum

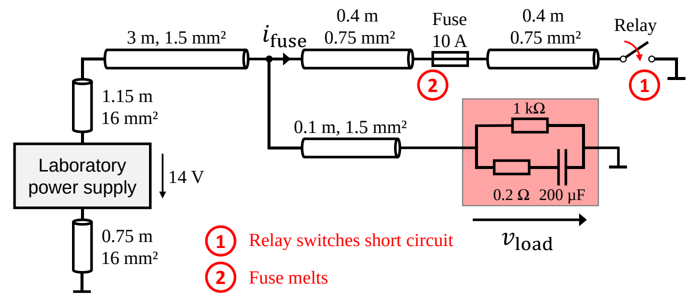

Fig. 8. Schematic of the melting fuse test bench for experimental validation

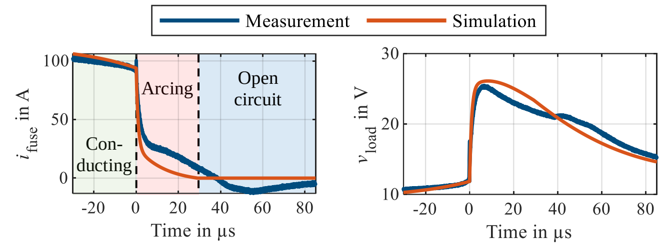

Fig. 9. Experimental validation of melting fuse model. Current through fuse (left) and voltage across the parallel RC load (right). Fuse melting starts at $t = 0$

current to not limit the fuse current (EA-PSI 9080-510). The fuse current i_{fuse} and the load voltage v_{load} are monitored when the 10 A fuse trips.

Fig. 9 shows the measured and simulated melting current over time. In the green region, at $t < 0$, the fuse is in conducting mode, the current heats up the fuse wire and the resistance rises. At $t = 0$, the fuse trips. The rapid current drop results in a voltage pulse reaching up to 26 V at the parallel RC load. The simulation results show a good agreement with the measurements.

C. Electronic Fuse Model

eFuses are often realized as special eFuse ICs and are available from several semiconductor manufacturers. These contain a power MOSFET for switching, together with a gate driver, protection, and some control logic, for example [30–33]. In contrast, discrete power MOSFETs may be used that are controlled and protected by a specific eFuse control IC, e.g. [34]. In the following, a special eFuse IC is assumed.

1) Overview: As most eFuse ICs only contain very basic wire protection logic, external microcontrollers can be used for running more complex fusing algorithms. Such fusing algorithms may have different complexity ranging from simple i²t-calculation [34] to wire temperature calculation based on sophisticated electro-thermal wire models [35]. Self-protection features protect the power MOSFET and trip the eFuse independently from an external control [5, 36, 37]. These protection mechanisms are discussed in the following.

a) Overtemperature protection: To protect the silicon die from thermal destruction, the fuse transistor opens once the junction temperature reaches a critical value (e.g., for the Infineon BTS50025-1TEA around 175 °C [31]).

b) Overcurrent protection: In case of a short circuit without significant current limiting components involved, a very large current may rapidly overheat an eFuse. Therefore, an additional protection mechanism is implemented in most eFuse ICs. When an overcurrent protection threshold I_{OCP} is exceeded, even for a very short time, the eFuse opens the power transistor. The level of this threshold compared to the fuse's nominal rated current I_{nom} differs from IC to IC. Typical factors of $I_{\mathrm{OCP}}/I_{\mathrm{nom}}$ range from 3.2 [31] up to 14 [30]. Some devices also offer adjustable thresholds for I_{OCP}, e.g., the ST VNF1048F [34].

Some eFuses offer additional protection functionality. Instead of instantly switching off once a current threshold is reached, they actively try to limit the current to a threshold by operating the MOSFET in its active region [33]. However, the MOSFET losses are significantly increased in this region and an overtemperature tripping follows.

c) Undervoltage protection: If the supply voltage of the fuse drops below a specified voltage, the output is turned off. Depending on the fuse, this behavior may be initiated below 6 V or less. Details like automatic restart and hysteresis can differ significantly between different ICs.

d) Overvoltage clamping: The switching of currents induces voltages across supply wires, load wires, and inductive loads. These may result in a transient overvoltage across an eFuse. To prevent the destruction of the MOSFET, its drain-source voltage must be limited to a safe level. Different approaches are possible. Many fuses feature an active voltage clamping by controlling the transistor gate accordingly, but external protection circuitry like diodes can also be used [10].

2) Modeling: A generalized eFuse model can be derived from the described functions and is depicted in Fig. 10. An eFuse IC, which includes the power stage and the self-protection features, is supported by an external microcontroller (MCU) used for the fusing algorithm.

For the MOSFET, a basic model [38] is used. The switching slopes depend on the gate driver and the parasitic capacitances C_{dg}, C_{ds}, C_{gs} of the transistor, sometimes given in the datasheet. As gate driver, a step voltage source V_{driver} with a serial resistor R_{g} is used. R_{g} has to be adjusted to meet the rise time of the switching process.

The protection thresholds can be implemented as functions controlling the voltage V_{driver}. The overvoltage clamping is modeled by the transient suppressor diode D_{ds} with appropriate breakdown voltage. Additional important elements can be the stabilizing capacitance C_{d} of the microcontroller or the protection diodes D_{d} between supply and ground (in Fig. 10).

3) Validation: The model has been validated in [22] based on measurements of an Infineon BTS50010-1TAD [39] eFuse. Model parameters were taken from the datasheet and measurements.

IV. Impact of Fuse Switching on Voltage Stability

A sudden fuse switching event can cause a large current gradient. Because of the wire inductances, high voltage transients may be induced in the supply system and affect the voltage stability of other loads. In this section, the impact of fuse switching on the supply voltages of other loads is analyzed. Melting and electronic fuses are compared.

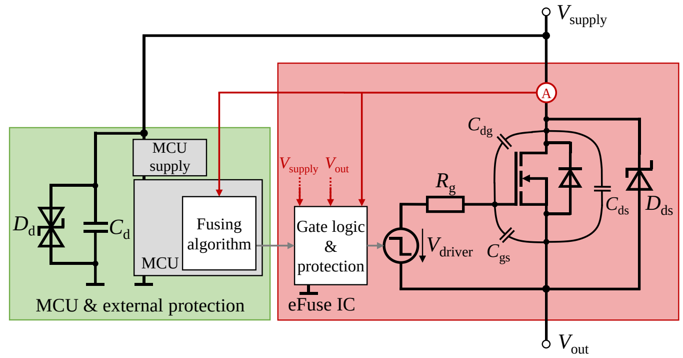

Fig. 10. Schematic of generalized electronic fuse model

A. Analysis of Power Supply System I

First, supply system I (refer to Fig. 2) is simulated for both fuse configurations. Fig. 11 shows the current i_1 of the faulty path (short at load 1) and the resulting voltage disturbance $v_{\mathrm{load,2}}$ at load 2. It can be seen that the eFuse switches off almost immediately after reaching its overcurrent protection threshold $I_{\mathrm{OCP,1}}$ of 150 A. The melting fuse limits the current only through its ohmic resistance until it finally melts after about 5.5 ms. Both switching events cause a voltage oscillation at load 2. The eFuse pulse slightly exceeds 29 V, while the melting fuse results in a peak of about 34 V because of the larger current that is switched off.

These supply voltage pulses might be potentially critical for functional safety. Component test standards like ISO 16750 [12] or individual manufacturer standards require components to withstand voltage peaks only up to a specific level. Beyond that specified level, proper function is not expected. In this paper, 27 V is considered the maximum acceptable supply voltage.

To reduce such voltage peaks, the system has to be designed accordingly. As an example, Fig. 12 shows the simulated overvoltage peak observed at load 2 depending on its capacitance $C_{\mathrm{load,2}}$. Different **e**quivalent **s**eries **r**esistances (**ESR**s) $R_{\mathrm{ESR,2}}$ are considered and (a) eFuse and (b) melting fuse configurations are compared. Large capacitances of more than 1 mF can significantly reduce the overvoltage in both configurations to less than 20 V if a small ESR is chosen. Therefore, critical overvoltages can be mitigated by adapting the input capacitor. Other system parameters that influence load voltage peaks are, for example, the PDU capacitance and the overcurrent threshold of eFuse 1.

B. Analysis of Power Supply System II

Next, the voltage stability of supply system II is investigated. Fig. 13 depicts the voltages $v_{\mathrm{load,2}}$ at load 2 and $v_{\mathrm{load,3}}$ at load 3 during the short circuit at load 1 for both fuse configurations. In contrast to system I, no significant overvoltage peaks result from the fuse tripping event, because of the larger capacitances in the loads and the PDU, which stabilize the voltages. However, when melting fuses are used, the voltage-drop along the supply wires results in a long undervoltage of less than 5 V for more than 150 ms. During the much faster reaction time of an eFuse, the voltage is still stabilized by the capacitors within its nominal operation range.

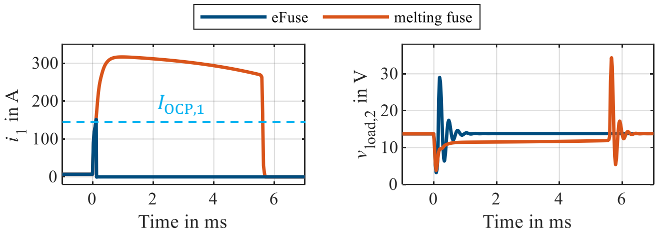

Fig. 11. Comparison of eFuse and melting fuse in faulty subsystem I. Simulated current of fuse 1 (left) and voltage at load 2 (right). Short circuit fault at t = 0

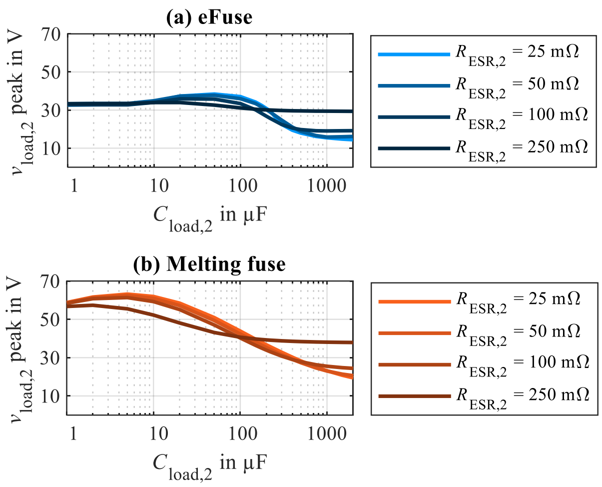

Fig. 12. Peak voltage at load 2 for different load capacitances and ESRs when using (a) eFuses and (b) melting fuses

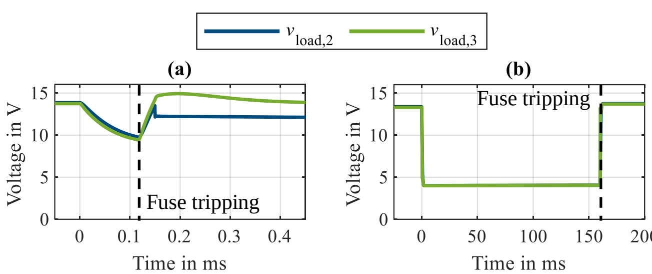

Fig. 13. Comparison of (a) eFuse and (b) melting fuse in system II. Simulated voltages at load 2 and 3. Short circuit fault at t = 0

In summary, significant over- and undervoltage peaks can result from short circuits combined with melting or electronic fuse switching. However, proper dimensioning of load and PDU capacitances can mitigate these pulses. Because of their hard current limitation, eFuse pulses tend to be less critical in comparison. As their fast reaction time also prevents critical undervoltages, eFuses are overall preferable to melting fuses in terms of voltage stability.

V. Impact of Fuse Switching on Other Electronic Fuses

Besides the impact of fuse tripping on the voltage levels in the overall power system, interactions with other fuses are also of interest. It is investigated, whether pulses created by fuse tripping can affect operation of other eFuses. First, the undervoltage resulting from a short may cause parallel eFuses to fail. Second, short current peaks initiated by fuse switching may trigger parallel fuses. Both phenomena are analyzed.

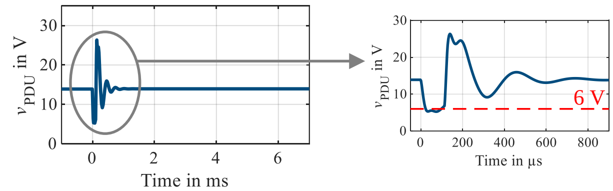

Fig. 14. Simulated PDU voltage in subsystem I when using eFuses and default parameterization. Short circuit fault at t = 0

A. Undervoltage Protection

For basic analysis, system I (refer to Fig. 2) is again simulated. Now, the effect of the short circuit on the PDU voltage v_{PDU}, which acts as the supply for eFuse 2, is of particular interest.

Electronic fuses need a voltage supply for operation. For example, the eFuse from [34] only operates above 6 V; an undervoltage causes a disconnection of the load. Contrary, a melting fuse is not affected by the PDU voltage. In Fig. 14, the PDU voltage v_{PDU} during the short circuit fault is depicted for the eFuse configuration. Because of the short circuit, a significant undervoltage can be observed for up to 100 µs reaching a minimum of about 5 V. Depending on the eFuse type, this might be low enough to trigger the internal undervoltage shutdown process, leading to a disconnection of load 2, although no fault is occurring in its load path.

Therefore, undervoltage shutdown needs to be prevented by either stabilizing the PDU voltage or by an eFuse that is robust against undervoltages. In system II, v_{PDU} is stabilized by the larger system capacitances and remains above 8 V.

B. Overcurrent Protection

Fuse switching events also produce current transients within the system. In this section, it is analyzed how these current pulses interfere with the overcurrent protection of other eFuses and can cause an unintended tripping.

In Fig. 15, the simulated current i_2 of system I is shown for melting and electronic fuse configurations. The tripping of fuse 1, caused by the assumed short circuit, creates a damped current oscillation with a large peak in fuse 2. While this short pulse only leads to a simulated temperature increase of about 1.5 °C in the melting fuse, it almost reaches the overcurrent protection threshold $I_{OCP,2}$ of the eFuse. Therefore, such transients may be able to turn off eFuses not directly affected by a wire short. Safety-critical loads can be disconnected. This is further analyzed in the following.

In an adapted scenario, the observed current pulse in system I might become critical, as the overcurrent limit of fuse 2 may be reached. For example, the power consumption of load 2 is now assumed to be lower, and therefore a thinner load wire with $A_2 = 0.75\ \text{mm}^2$ and a 10 A eFuse with $I_{OCP,2} = 75$ A are used. The result of this configuration is shown in Fig. 16. The peak current of i_2 for this adapted scenario is shown over the capacitance value $C_{load,2}$. Furthermore, different ESRs ($R_{ESR,2}$) are simulated. A current peak below 40 A is reached for small capacitances of 10 µF and less. With rising capacitance, the current pulse also rises until a maximum is reached at about 300 µF. Larger capacitances still result in a significantly large current pulse above the assumed shutdown threshold of 75 A,

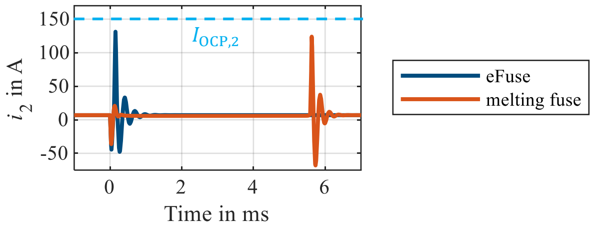

Fig. 15. Comparison of current pulses in system I. Simulated current of fuse 1 (left) and fuse 2 (right). Short circuit fault at t = 0

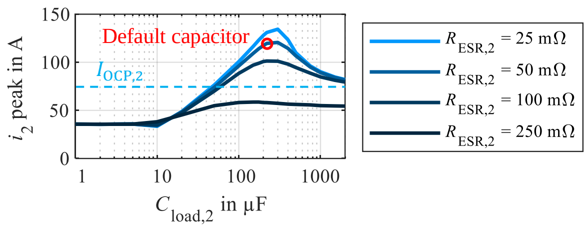

Fig. 16. Simulated peak current through eFuse 2 in system I for different load 2 capacitances and ESRs. $A_2 = 0.75\ \text{mm}^2$ and $I_{OCP,2} = 75$ A

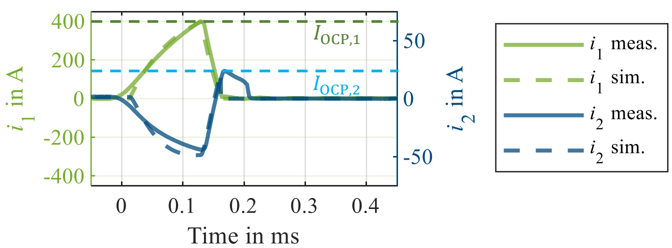

Fig. 17. Simulated and measured currents of system II during short circuit scenario with eFuses. Short circuit at t = 0

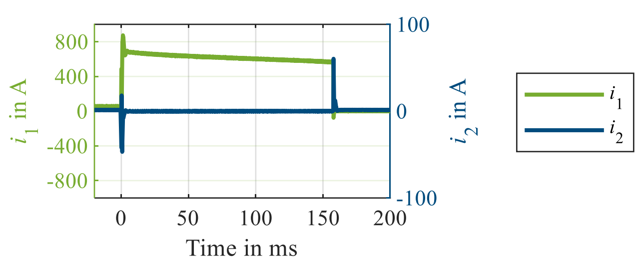

Fig. 18. Simulated currents of system II during short circuit scenario with melting fuses. Short circuit at t = 0

as long as the ESR is low. A large ESR dampens the current oscillation. For an ESR of 250 mΩ the current amplitude remains below 75 A. This reveals a conflict of objectives. Large load capacitors with low ESR are beneficial for a stable supply voltage and electromagnetic compatibility but might amplify transient current oscillations initiated from fuse tripping.

The possibility of unintended tripping of eFuses in realistic supply networks is further analyzed in system II. The simulated current pulses show that the switching of eFuse 1 triggers the overcurrent protection of eFuse 2 (Fig. 17). Therefore, load 2 gets disconnected because of a fault at a parallel load. As this newly discovered behavior can be very critical in supply systems with electronic fuses, that have to be highly reliable, it has been validated in the laboratory setup (refer to section II-C). The measurements shown in Fig. 17 (dashed lines) confirm the findings from the simulation; the switching transient of eFuse 1 leads to an overcurrent shutdown of eFuse 2.

Finally, currents from a melting fuse configuration are shown in Fig. 18. Here, no unintended tripping occurs as the resulting current pulse i_2 is too short to melt the fuse wire.

VI. Discussion

In the previous sections, several challenges have been analyzed that arise with the introduction of eFuses, especially for application in fail-operational automotive power supply systems. The transients from wire shorts and subsequent fuse tripping can cause overvoltage pulses within the system and undervoltages in the eFuse supplies. Other eFuses can trip because of high current transients.

Critical overvoltages in loads can generally be caused by both melting and electronic fuse switching, especially after high current short circuit faults. However, melting fuses tend to be more critical because they do not actively limit the maximum fault current. Moreover, these overvoltages can be mitigated by selecting large electrolytic capacitors with low ESRs. A total capacitance of several millifarads in typical automotive supply systems should usually be sufficient to stabilize the supply voltages. Simulations can be useful to optimize the size of the capacitors.

Furthermore, unlike melting fuses, eFuses need a minimum voltage for normal operation. As shown in section V, nearby short circuit faults may result in undervoltage. To avoid undervoltage shutdown of eFuses, the PDU voltage must be stabilized by, for example, a large capacitance. Furthermore, eFuses shall be tolerant against undervoltages.

Switching pulses, that trigger the overcurrent protection threshold of other eFuses and therefore result in unintended tripping, seem to be the largest challenge. Especially low power components, which are protected by eFuses with low tripping currents, might be affected.

Remedial actions must be taken to manage the critical current pulses that may cause tripping of other eFuses. These actions might include:

- Large PDU capacitances provide an additional low-impedance path for the switching currents and therefore reduce the current peaks in other network branches. Small load capacitances combined with high ESRs help with dampening critical current resonances. However, practical options might be limited here because of voltage stability and other requirements, for example, electromagnetic compatibility.
- Short circuit currents in the supply network should be minimized. The largest network fault currents are to be expected from high current loads, which are protected by fuses with large overcurrent thresholds. Reducing these thresholds is, however, only possible if a sufficient distance to nominal load current spikes can be ensured.
- If critical current pulses in a network cannot be further reduced, the eFuses that might be affected, need to be

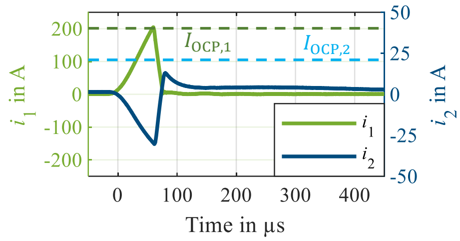

Fig. 19. Measured currents during short circuit scenario with $I_{OCP,1} = 200$ A. Short circuit at $t = 0$

over-dimensioned. The overcurrent protection threshold I_{OCP} of such fuses needs to be higher than the expected transients.

- In general, a slower switching speed of the power transistor would reduce the current gradient and, therefore, the resulting transients. However, a practical realization is not expected to be feasible, as safety demands might require very fast disconnection of faults. Also, slower switching of large short circuit currents increases the thermal losses inside the semiconductor.
- Finally, unintended tripping may be tolerated for loads that are not safety-relevant. In this case, an unintended tripping could be detected by evaluating the individual fuse currents and switching orders to subsequently turn the affected eFuse on again.

An exemplary remedial action for the parasitic triggering in system II is demonstrated by the measurements depicted in Fig. 19. Here, the eFuse 1 is replaced by an eFuse with an overcurrent protection of $I_{OCP,1} = 200$ A. It can be seen that the adaption reduces the current peak of i_2 to about 13 A, which does not trigger the 20 A threshold of fuse 2. Therefore, an uninterrupted supply of load 2 is now possible.

Compared to eFuses, melting fuses are not affected by such overcurrent pulses. However, because of long tripping times, critical undervoltages are more likely to occur with melting fuses.

VII. Conclusion

In this paper, the impact of eFuses on the propagation of voltage and current pulses in automotive power supply systems has been analyzed and compared to conventional melting fuses. First, simulation models for melting and electronic fuses have been presented. These focus on the melting and switching behavior, respectively, and are optimized for investigating transients from tripping fuses.

Based on simulations of two exemplary power supply systems, several challenges have been analyzed. It has been shown, that the switching of high currents can produce critical voltage peaks at loads. These can be stabilized by sufficiently large capacitances. To ensure the reliable operation of eFuses, the supply voltages in the power distribution units also need to be stabilized to prevent undervoltage shutdown of an eFuse. Another aspect that has been identified is the unintended tripping of eFuses due to current peaks. The disconnection of high short circuit currents can produce large current pulses within the remaining system that can trigger the overcurrent protection thresholds of other eFuses with low current ratings. Other loads far from a faulty branch can be disconnected and redundancy concepts fail. Finally, this paper gives some guidelines for avoiding unintended triggering when using eFuses.

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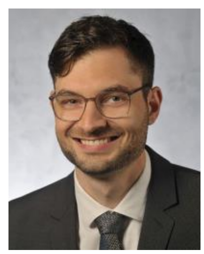

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