Voltage Stability of Automotive Power Supplies During Tripping Events of Melting and Electronic Fuses

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***Abstract*—Future automotive power supply systems must be fail-operational. Even short voltage disturbances at safety-relevant components due to switching events may be critical. The tripping of melting fuses and semiconductor-based electronic fuses (eFuses) cause serious switching events that may affect the overall power supply system. While non-automated vehicles were mainly equipped with melting fuses and voltage drops could be tolerated, future automated vehicles will be equipped with eFuses to meet functional safety requirements. Especially the behavior and impact of eFuses is not well understood today. In this paper the influence of switching events caused by tripping melting fuses and eFuses on the power supply voltage stability is investigated and both fuse types are compared. For this purpose, simulation models of automotive melting fuses and eFuses were developed and validated. The new models, in contrary to the known fuse models, focus on accurate modeling of the tripping behavior. Based on simulation and measurements, both fuse types are analyzed and their impact on other system components is investigated. It has been found that both melting fuses and eFuses might produce significant over-voltages at other loads. Parameter studies show, how to mitigate critical over-voltages.**

Keywords—automotive power supply, eFuse, electronic fuse, melting fuse, simulation, smart fuse, transient, voltage stability

I. Introduction

Highly reliable power supply is essential for future automated vehicles. The supply systems must be fail-operational, this means they must ensure operation of critical components even in the case of faults [1]. In case of an overloaded wire failure, fuses should protect the power supply system by interrupting the circuit and isolating the faulty branch sufficiently quickly, ideally allowing the remaining supply system to operate without interruption. The branch overload, often a short, might cause a sudden drop of the supply voltage in the supply system and trigger complex oscillations, while the interruption process might cause significant over-voltages.

In the past, the wiring harness has been protected against overload currents by melting fuses. Here, a thin wire melts at a defined current load profile. These fuses are increasingly replaced by electronic semiconductor fuses, also called eFuses or smart fuses. These enable flexible overload switching together with advanced operating and diagnosis functions [2]. Both fuse types can generate very fast switching events.

Research on voltage stability and optimization of automotive supply systems can be found in [3]-[6]. These investigations primarily focus on the static consequences of general faults or slow processes in the range of milliseconds or longer. The results cannot be applied to the fast switching of fuses. A method for transient stabilization of the supply system using passive filters has been proposed in [7]. The known publications put a focus on general supply faults and dynamic loads, not on fuse switching. Today it especially is unclear, what specific transient impact eFuse switching has to other components, how eFuses react to disturbances, and how this behavior compares to conventional melting fuses.

Melting fuse and eFuse switching can be investigated by simulation. For this purpose, accurate models of the switching processes for both melting fuse and eFuse are necessary. For melting fuses, this includes modeling of the arcing process that occurs during the melting of the fuse wire. An approach is proposed in [8] and adapted in [9]. However, this approach is not sufficient for arbitrary operating points of the fuse. The thermal behavior of melting fuses before triggering can be adapted from existing approaches, e.g. [10]. eFuses consist of a switching power transistor, usually a MOSFET [2]. The switching behavior of a MOSFET is well understood and existing simulation approaches, e.g., [11], can be used. As shown in [9], additional circuitry may influence the transient behavior and needs to be considered.

In this paper melting fuse and eFuse switching are analyzed by measurements and simulations. The existing modeling approaches are improved and extended to enable accurate transient simulations of switching behavior within supply systems. The proposed fuse models are individually validated using laboratory measurements. Finally, the models are used to investigate the transient impact fuse switching can have on other on-board components and how melting fuse switching differs from eFuse switching. Methods for mitigation of critical over-voltages are analyzed and discussed. The contribution closes with a conclusion and an outlook.

II. Power Supply System and Fault Modeling

In this section, the relevant models for the transient simulation of automotive power supply systems are presented. First, the modeling of basic components for energy storage and distribution as well as considered faults are shortly summarized. Then, the developed models of melting and electronic fuses are explained in detail. All models are implemented in MathWorks' MATLAB/Simscape and simulated with a variable time step.

A. Basic Power Supply Components

The basic components of power supply systems relevant for fault investigations are battery, wires, loads and faults. Additional components such as generator or DC/DC converter are not discussed here as they do not influence the overall findings of this contribution. Different modeling approaches and aspects for transient behavior are discussed in [9]. In this paper, load models are simplified to a resistor in parallel to a capacitor with **e**quivalent **s**eries **r**esistance (ESR). These represent the power consumption and input capacitance for voltage stabilization of an arbitrary **e**lectronic **c**ontrol **u**nit (ECU). As the wire's inductances are crucial for the transient behavior of the overall supply system, all wires are modeled using an RL serial circuit representing the resistance and the approximated wire inductance (here 1 µH per 1 m wire length). Batteries are modeled as a voltage source with a resistor in series. [9]

B. Fault Modeling

Only short circuit faults are to be considered, as they trigger fuses and therefore produce transient disturbances. These are modeled by a simple switch that switches from a very high resistance (e.g. 1 MΩ) to a very low resistance (e.g. 1 µΩ). [9]

C. Conventional Melting Fuses

For the modeling of an automotive melting fuse, three operating modes have to be considered: the conducting mode where the fuse behaves as a temperature-dependent resistor, the arcing mode that is initiated if the fuse wire reaches its melting temperature, and the open mode that is just an electric open.

1) Conducting Behavior: The basic thermal model of a melting fuse's behavior given in [10] is sufficient for the conducting mode. The temperature of the fuse wire is calculated using a thermal equivalent circuit consisting of four serial RC elements. Knowing the temperature of the fuse, its ohmic resistance can be determined. As high temperatures cannot be modeled well with only a linear temperature coefficient α, an extension with a second order coefficient β and an exponential term is used here. Thus, the fuse resistance R_{fuse} is calculated as follows:

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

R_{cold} is the resistance at 25 °C. ΔT is the temperature deviation and A and B are the exponential coefficients. The temperature coefficients and RC parameters of the thermal equivalent circuit need to be individually determined for every fuse type. In this contribution, the basic parameterization from [10] is adopted and A and B are determined using measurements of the specific fuse type. Particularly important for accurate transient switching simulation of the fuse is its resistance at the melting temperature (400 °C [10]), as it represents the initial condition for the subsequent arcing state. Exemplary, for a 10 A ATO fuse the initial melting resistance $R_{\text{fuse}}(400\ °\text{C}) \approx 87\ \text{m}\Omega$ has been determined.

2) Arcing Behavior: After melting, an arcing process is initiated causing the current to fall and resulting in a voltage peak across the contacts of the fuse due to the system's inductances. To approximate this complex (and in part stochastic) behavior of melting fuses, [8] proposes a switchable RC circuit, that is connected in series with the resistance R_{fuse}. When the fuse reaches its melting temperature one switch opens and the other switch closes. Given the right parameterization of the arcing circuit, this approach offers a good reproduction of the behavior of automotive fuses, as shown in [9]. However, a constant set of RC parameters, as used in [8] and [9], only works well for one specific operating point. To achieve a model, that is applicable for a wide range of operating points, i.e., different short circuit current levels, an extension is introduced in this paper. The parameters R_{arc} and C_{arc} of the arcing circuit are assumed to be a function of the current I_{melt} during the state transition from conducting to arcing behavior.

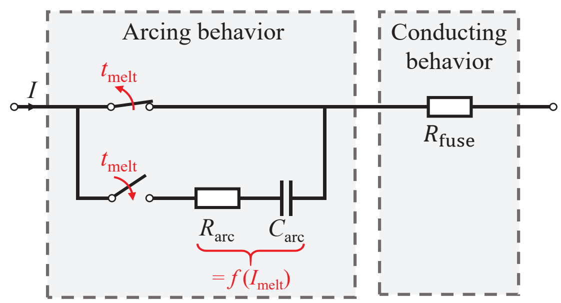

Fig. 1: Model for the electrical behavior of an automotive melting fuse

The aim is to find a mathematical expression for the arcing parameters depending on the melting current. This can be done by conducting several test measurements at different operating points for each fuse type to be parameterized. Then, for each test measurement a simulation is performed and the fuse parameters are adjusted to achieve a good fit to the measurement. Finally, a curve is fitted to the obtained points, allowing the parameter approximation for any arbitrary melting current. For example, the resulting parameters of a 10 A ATO fuse, as depicted in Fig. 2, can be calculated by:

$$\begin{aligned} C_{\text{arc}} &= e^{\frac{I_{\text{melt}}}{35}} - 1 \qquad (\text{in } \mu\text{F}) \\ R_{\text{arc}} &= \max(-4.5 \cdot 10^{-3} \cdot I_{\text{melt}} + 1.1, 0.2) \qquad (\text{in } \Omega) \end{aligned} \tag{2}$$

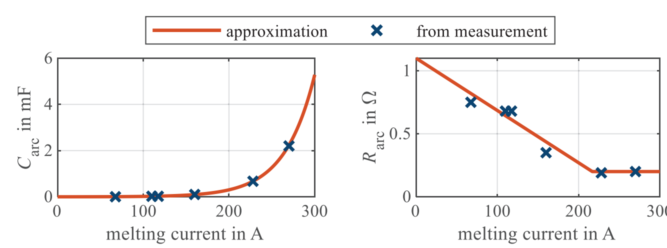

Fig. 2: Arcing circuit parameters of a 10 A ATO fuse for different melting currents

3) Validation: The described fuse model has been validated in a simplified laboratory setup. Fig. 3 shows the test bench. The melting fuse (Littelfuse ATO 10 A) can be short circuited to ground by a relay. An exemplary RC load is connected in a branch parallel to the fuse. A laboratory power supply with maximum current of 510 A is connected with wires of about 5 m total length. A voltage of 14 V is chosen, representing a typical on-board voltage during driving.

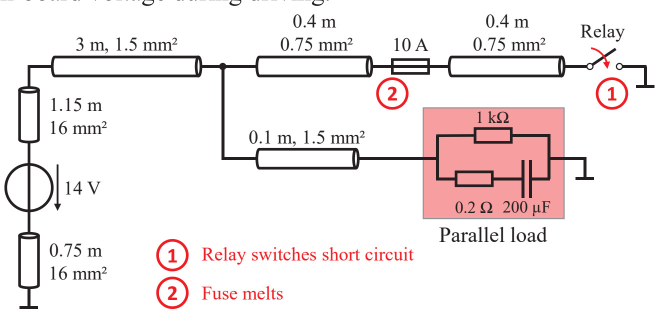

Fig. 3: Schematic of the test bench for melting fuse validation

The relay short circuits the fuse's branch causing the fuse to melt a few milliseconds later. The measured and simulated impact of this switching process on the voltage stability of the adjacent load is depicted in Fig. 4 along with the voltage across and the current through the fuse terminals. The high current slope of the switching process in combination with the wire inductances cause a significant voltage peak of about 26 V at the load. The simulation results are very close. There is a larger deviation between simulation and measurement for the short fuse voltage peak around $t = 0$. However, this high frequency pulse has no significant impact on the power supply of other components in the system. Therefore, a more accurate modeling of this peak is not required to investigate the voltage stability of the system.

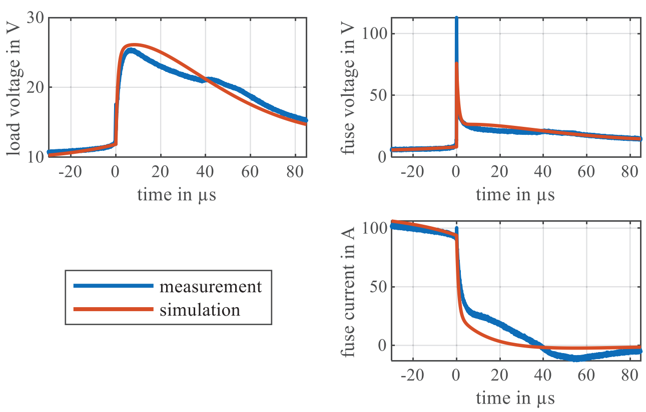

Fig. 4: Validation results of 10 A ATO melting fuse. Voltage at parallel load (left); voltage across and current through fuse (right). Fuse melting at $t = 0$.

D. Electronic Fuses

Electronic fuses are offered by different manufactures (e.g. [12] and [13]). In general, they consist of a power transistor with driver, protection and diagnosis functions built into one IC. Furthermore, they may require additional circuitry that influence the transient behavior. In this section, relevant aspects to simulate the influence of switching events on the supply system are discussed, followed by the presentation of a specific eFuse model and its validation.

1) Triggering algorithm: eFuses offer current measurement functionality, that allow for advanced diagnosis and triggering algorithms to be executed by a separate **m**icro**c**ontroller **u**nit (MCU). For example, in combination with thermal wire models this might enable cross section reductions of the wiring harness [14]. As this paper focuses on the switching process, a thermal model is not considered.

2) Transistor Modeling: The power transistor, usually a MOSFET, is the key component of an eFuse. It is located in the fuse's current path and is responsible for the switching operations. A basic MOSFET model [11] and a simple gate driver consisting of a pulse voltage source and a series gate resistance R_g is depicted in Fig. 5 and has been implemented. The most important aspect regarding the switching behavior is the transistor's switching slope, which determines the current derivative responsible for the voltages induced in the wire inductances. In the model the gate resistance R_g and the gate-source capacitance C_{gs} are adjusted to match the desired switching slope based on measurements and datasheet values.

3) Self-Protection Mechanisms: Besides the wire protection behavior that is externally programmable (see subsection 1), eFuses have implemented several intrinsic protection mechanisms that trigger the fuse independently from external control signals. These can include a short circuit protection which automatically triggers the fuse once a specific current-threshold is reached and an under-voltage protection that is triggered once the supply voltage drops below a specific level.

Furthermore, over-voltage protection aims to mitigate voltage pulses that could destroy the fuse or control circuits by clamping the supply voltage and/or the drain-source voltage. This behavior is modeled by diodes with a specific breakdown voltage.

4) Additional Circuitry: In addition to the mentioned components, electronic fuses or the microcontroller might require further circuitry that can influence the transient behavior of the supply system and therefore needs to be considered in a simulation, e.g., stabilizing capacitors or external diodes for over-voltage protection from supply voltage to ground (C_d and D_d in Fig. 5).

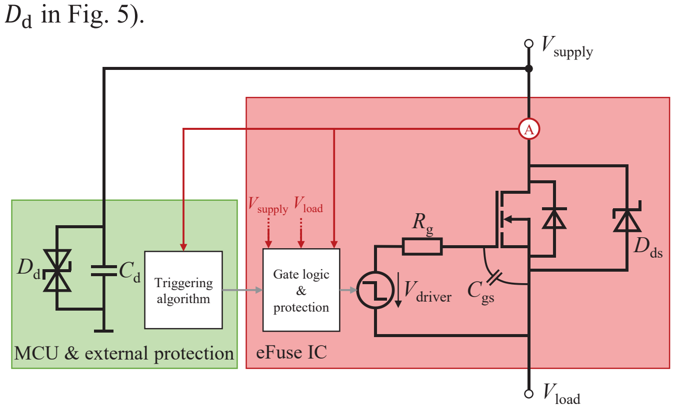

Fig. 5: Schematic of generalized electronic fuse model

5) Practical Example and Validation: The structure from Fig. 5 must now be parameterized for the specific eFuse model investigated here: BTS50010-1TAD from Infineon [12]. For the MOSFET $R_{\mathrm{ds(on)}} = 1\ \mathrm{m\Omega}$ and $C_{\mathrm{gs}} = 80\ \mathrm{pF}$ are used. The fuse automatically switches off if the current exceeds 200 A for longer than 16 µs. The drain-source voltage is clamped to 35 V. The MCU is supplied by a voltage regulator with an input capacitance of $C_{\mathrm{d}} = 100\ \mathrm{\mu F}$. The fuse is triggered by the MCU if the current exceeds a given threshold for more than 1 ms. This external triggering includes a delay from the external logical switching signal to the actual switching of the transistor of at last 100 µs. The measured switching behavior of the BTS50010-1TAD can be achieved with a two-stage gate control (gate resistance starting at $R_{\mathrm{g}} = 70\ \mathrm{k\Omega}$ and jumping to $R_{\mathrm{g}} = 100\ \Omega$ after 180 µs). To validate this model, the test bench depicted in Fig. 3 is operated with the eFuse instead of the melting fuse. As shown in Fig. 6, the simulation of this scenario represents the measured fuse behavior very well. Fig. 6 also shows a one-stage gate control with a constant gate resistance of $R_{\mathrm{g}} = 100\ \Omega$ compared to the two-stage control mentioned above. As can be seen, this approach is equally good in determining the over-voltage at the parallel load and is therefore used within this contribution.

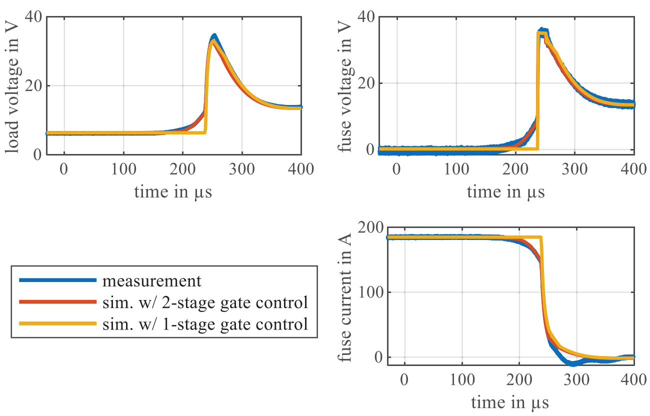

Fig. 6: Validation of eFuse model for Infineon BTS50010-1TAD. Voltage at parallel load (left); voltage across and current through fuse (right). Fuse triggering at $t = 0$. Comparison of modeling a two-stage gate control vs. a one-stage gate control

III. Comparison in Simplified Network

The validated models are used for comparison of melting fuses and electronic fuses regarding their influence on the transient voltage stability.

A. Simplified Network

For the investigations in this chapter the simplified power supply system depicted in Fig. 7 is used. This network consists of a 14 V battery and two exemplary parallel loads each protected by a 10 A melting fuse or eFuse. This might be a possible subsystem of a ring or bus topology with several zone controllers. The default parameterization includes an internal battery resistance $R_{\mathrm{i}} = 5\ \mathrm{m\Omega}$, load resistances $R_{\mathrm{load,1}} = R_{\mathrm{load,2}} = 2\ \Omega$, load capacitances $C_{\mathrm{load,1}} = C_{\mathrm{load,2}} = 220\ \mathrm{\mu F}$ with an ESR's of $R_{\mathrm{esr,1}} = R_{\mathrm{esr,2}} = 50\ \mathrm{m\Omega}$. The supply wire with a cross section of 35 mm² has a length of $l_{\mathrm{supply}} = 5\ \mathrm{m}$ and both loads are connected by a wire of length $l_{\mathrm{load,1}} = l_{\mathrm{load,2}} = 2\ \mathrm{m}$ and cross section of 0.75 mm². The fault scenario to be investigated is a short circuit of load 1 (red dashed line, Fig. 7).

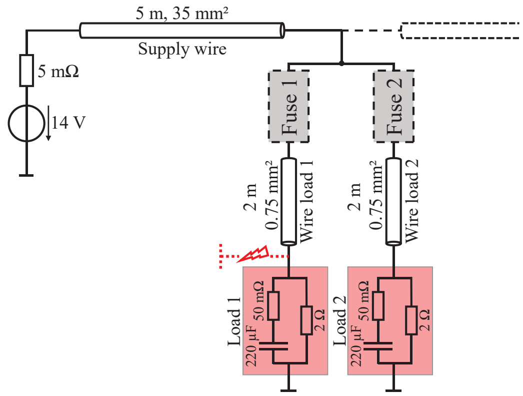

Fig. 7: Simplified power supply system for fuse comparison and parameter analysis

B. General Comparison

The described short circuit scenario is simulated with 10 A melting fuses and with eFuses using the proposed models. Fig. 8 shows the current through fuse 1 and the resulting voltage disturbance at load 2 for both cases. As can be seen, the eFuse is reacting much faster and switches off once the current exceeds its self-protection limit of 200 A. The melting fuse takes more than 2 ms for tripping. Both switching events cause a transient voltage peak at load 2 reaching an amplitude of about 29 V (eFuse) and 25 V (melting fuse), respectively. This can be explained by the different current levels at the beginning of the switching slope. As the melting fuse's resistance increases significantly while heating up, the current already decreases before reaching the melting point. Therefore, the $\mathrm{d}I/\mathrm{d}t$ that causes the overvoltage is lower in comparison to the eFuse.

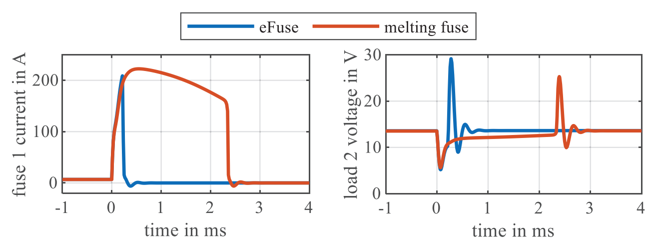

Fig. 8: Comparison of melting fuse and eFuse during short circuit fault at load 1. Current of fuse 1 (left) and resulting voltage disturbance at load 2 (right). Short circuit fault at $t = 0$

C. Analysis of Selected System Parameters

Additionally, the influence of selected system parameters on the transient voltage of load 2 is analyzed for both cases (melting vs. electronic fuse). First, the wire length $l_{\mathrm{load,1}}$ of load 1 is varied between 0.25 m and 4 m. This influences the resistance of the short circuit path and therefore the potential short circuit current. The resulting voltage peaks at load 2 during fuse switching are depicted in Fig. 9. In case of melting fuses, a shorter load wire leads to a higher short circuit current that in turn causes a higher voltage peak of up to 37 V during the switching. Using eFuses, however, all wire lengths of 2 m and below result in approximately the same over-voltage of about 30 V, due to the over-current protection which doesn't allow the current to significantly exceed 200 A. Only the wire lengths of 3 m and 4 m don't trigger the internal current limitation and therefore result in a different voltage at load 2 and show a larger trigger delay. Note that the different voltages at $t = 0$ when using eFuses are a result of the transient voltage undershoot caused by the short circuit. In contrast, as melting fuses take significantly longer before tripping, the undershoot is already over when the melting process starts at $t = 0$ (also refer to Fig. 8). The relationship between the length of wire 1 and the maximum voltage at load 2 is also depicted in Fig. 10 (left) for both fuse types. The melting fuse causes a larger voltage peak at the adjacent load for wire lengths of less than 0.6 m, while the eFuse causes larger voltage peaks for length above 0.6 m.

Next, the influence of the load capacitance on the observed over-voltage is investigated. With default wire lengths, the capacitance of load 2 is now varied from 1 µF to 2 mF. The resulting peak voltages are depicted in Fig. 10 (right). As can be seen, for both types of fuses the capacitance has a significant influence on the experienced over-voltage. Larger capacitances of 1 mF and above reduce the voltage peak to less than 20 V. Using an eFuse the voltage reaches up to 38 V at a load capacitance of about 20 µF, while using a melting fuse, a peak voltage of up to 59 V can be observed at a capacitance 2 µF. This can be explained by different resonant behavior of the system depending on the fuse type.

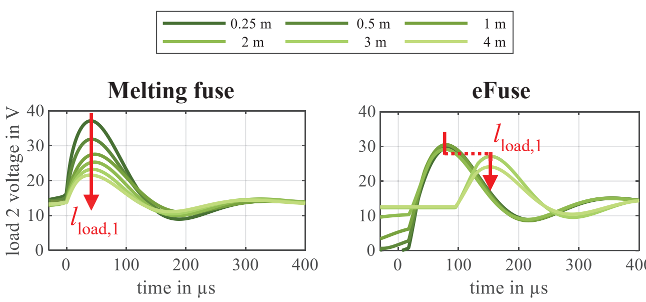

Fig. 9: Voltage at load 2 during switching of fuse 1 with varying load 1 wire length. Fuse triggering at $t = 0$

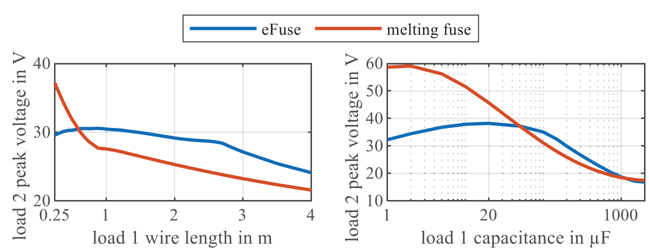

Fig. 10: Peak voltage at load 2 during switching of fuse 1 for different load 1 wire lengths (left) and load 1 capacitances (right). Comparison of eFuse and melting fuse

Besides the capacitance of the load, the capacitor's ESR also has a notable influence on the resulting over-voltage at the load. Fig. 11 shows a parameter study where the peak voltage of load 2 in the short circuit scenario is evaluated for different capacitances and ESR values. It can be seen that, for both eFuse and melting fuse, a low ESR can be advantageous or detrimental for reducing over-voltages. A large ESR is beneficial to dampen the resonance observed at about 2 µF for the melting fuse and at 20 µF for the eFuse (see Fig. 10 (right)). Contrary, with larger capacitances, a large ESR increases the overall impedance of the capacitor and limits its ability to stabilize the load voltage.

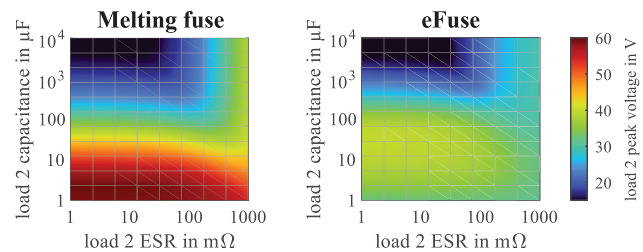

Fig. 11: Peak voltage at load 2 during switching of fuse 1 depending on capacitance and ESR of load 2. Comparison of melting fuse (left) and eFuse (right)

IV. Discussion

As seen in the previous chapter, switching events of both melting and electronic fuses can create transient over-voltages at other loads with amplitudes above 30 V. Depending on the specification of the respective components, these could be potentially critical. For example, according to the VW 80000 [15] standard, voltage pulses higher than 27 V are beyond test requirements for electrical components. Therefore, these voltage pulses shall be prevented to ensure proper function. This can be achieved by, e.g., choosing a sufficiently large input capacitor with low ESR. As the simulation enables the investigation of the transient voltage stability for a large number of different scenarios, it is a valuable tool for designing a highly reliable and cost-effective power supply system.

V. Conclusion

In this paper, a comparison between melting fuses and electronic fuses on the voltage stability of automotive power supply system has been presented. For this investigation, suitable simulation models have been developed and described. It has been shown that tripping of both fuse types may cause transient over-voltages in the power supply which are beyond current specifications. Stabilizing capacitors can reduce these voltage overshoots. Based on the developed models and findings, further research can be done on comprehensive investigation methods and optimization approaches to ensure high reliability of future power supply systems.

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