Transient Analysis of Switching Events and Electrical Faults in Automotive Power Supply Systems

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Abstract

Highly automated driving increases the requirements on the transient voltage stability of automotive power supply systems. Simulations are a necessary tool to consider this aspect in the early stages of development. In this paper, suitable simulation approaches are presented in order to investigate the transient effects of switching operations and faults on the voltage stability of other components. After a validation of the presented models using laboratory measurements, the influences of load parameters and the different effects of conventional melting fuses and electronic semiconductor fuses are investigated based on an exemplary 12V/48V power supply system.

Kurzfassung

Durch das hochautomatisierte Fahren steigen die Anforderungen an die transiente Spannungsstabilität von Kfz-Energiebordnetzen. Um diesen Aspekt im frühen Entwicklungsstadium berücksichtigen zu können, sind Simulationen notwendig. In diesem Paper werden geeignete Simulationsansätze präsentiert, um die transienten Auswirkungen von Schalthandlungen und Fehlern auf andere Verbraucher untersuchen zu können. Nach einer messtechnischen Validierung der vorgestellten Modelle werden anhand einer beispielhaften 12V/48V-Bordnetztopologie die Einflüsse von Lastparametern sowie die unterschiedlichen Auswirkungen von konventionellen Schmelzsicherungen und elektronischen Halbleitersicherungen untersucht.

1 Introduction

The requirements on vehicle's functional safety will increase because of highly automated driving. Therefore, future power supply systems must be fail-operational, ensuring a safe operation even in the case of an electrical fault [1]. These new requirements can become a challenge in the development stage, as common approaches and current standards will not be sufficient anymore.

Transient current or voltage pulses can be caused by intended switching operations or unintended failures. Such transient pulses propagate through the whole power supply system and must not compromise the function of safety-critical components. To illustrate this problem, Figure 1 shows a simplified 12V/48V power supply system which uses a bus topology, power distribution units (PDUs) and generalized loads. As depicted, transient faults occurring somewhere in the system may lead to critical under- or over-voltage at other, potentially safety-relevant loads. To analyze the transient behavior and the complex interactions in the power supply system simulations are an essential tool. Simulations enable comprehensive investigations of a variety of scenarios and can therefore be used for the assessment of new power supply topologies in all stages of development.

Automotive power supply systems consist of several different components that provide, distribute, convert, and consume energy. Accurate models are needed to simulate the electrical behavior of all relevant components, such as batteries, generators, wires, switches, fuses, converters, and loads. Several model libraries for power supply simulation have been proposed in the past, e.g. [2]-[6]. However, these libraries were not optimized for transient pulses and switching events. As these events are very fast, additional effects like wire inductances need to be considered too. Additionally, transient behavior of switching events, including effects like arcing, and realistic fault models have to be implemented. These aspects have been investigated in [7].
This paper analyzes critical aspects regarding the transient voltage stability within supply systems. First, section 2 presents the relevant fault and component models used for the simulative investigations. Based on an exemplary 12V/48V power supply system, introduced in section 3, an experimental validation of the presented models is performed in section 4. In Section 5, the models are then used to analyze the transient voltage stability of the exemplary system. In particular, parameter variations are performed and a comparison of electronic and melting fuse is made. The paper closes with a conclusion and an outlook.

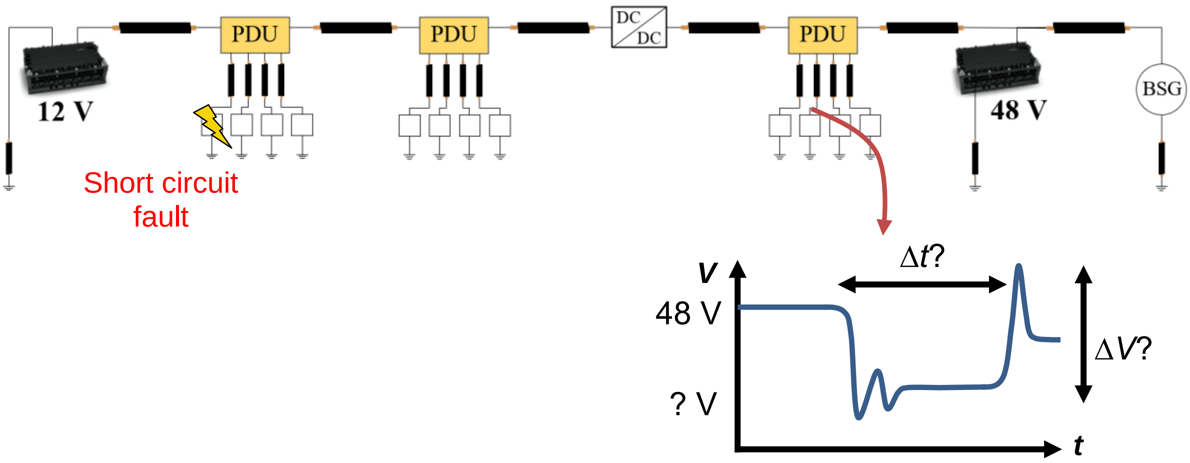

Figure 1: Generalized supply system with bus topology utilizing power distribution units (yellow) and exemplary depiction of short circuit fault

2 System Modeling

This section gives a brief overview of the fault and component models used for the analysis in this paper. A detailed description can be found in [7].

2.1 Fault Modeling

Transient faults such as short or open circuit faults within the wiring harness are especially relevant regarding their effects on the transient voltage stability. These faults may lead to large current slopes that result in large induced voltages. When modeling open circuit faults, arcing between the opening contacts needs to be considered. A short circuit, on the other hand, can be modeled with sufficient accuracy as an ideal jump from high to low resistance.

2.2 Component Modeling

The system components that are relevant in this contribution are described in the following.

2.2.1 Battery

Many different approaches exist for modeling the electric behavior of batteries. The model structure used in this paper is depicted in Figure 2 and consists of an internal resistance $R_{\mathrm{in}} = R_1 + R_2 + R_3$ and a parasitic inductance L. The RC elements represent the dynamic behavior due to internal chemical processes. According to [5], typical values for an 80 Ah lead-acid battery are $R_1 = R_2 = 3\ \mathrm{m\Omega}$, $R_3 = 10\ \mathrm{m\Omega}$, $C_1 = 1\ \mathrm{F}$ and $C_2 = 300\ \mathrm{F}$.

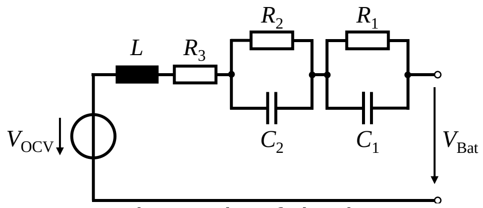

Figure 2: Schematic of the battery model

2.2.2 Generator

The implementation of the generator model used in this paper is based on [2], representing a three-phase, self-excited synchronous machine with an integrated rectifier. The dynamic behavior of the generator depends on the L/R time constant of its windings which can be as high as 100 ms.

2.2.3 Wiring

Each wire of the system's wiring harness is represented by an equivalent circuit. Besides its ohmic resistance given by its cross section A and its length l, parasitic inductance needs to be considered. Here, an approximate value of $L' = 1\ \mathrm{\mu H/m}$ is used. Parallel capacitances and conductances are very small and do not need to be considered when investigating supply voltage stability.

2.2.4 DC-DC Converter

DC-DC converters are responsible for the power flow between different voltage levels. A behavioral model can be used that does not consider the switching power electronics but uses voltage and current ratios and conservation of energy. Furthermore, input and output filters consisting of capacitors or inductors influence the transient behavior and need to be considered.

2.2.5 Loads

Modern vehicles include a variety of electronic control units (ECUs) and other electric loads. Accurate modeling of their time-variant behavior can be complex, however, for investigation of the power supply's transient behavior, it is possible to define stationary operating points of the loads that can then be modeled using passive elements. A general ECU model consists of a resistor that represents its power consumption and a parallel input capacitor including its equivalent series resistance (ESR) [5].

2.2.6 Melting Fuse

The function of a conventional melting fuse is to interrupt the current path in case of an overcurrent in order to thermally protect its subsequent wire. If the temperature is below its melting temperature, the fuse acts like a temperature-dependent resistor (conducting behavior). A common approach to determine the fuse's temperature is by modeling it as a thermal equivalent network of multiple serial *RC* elements representing its thermal capacity and thermal resistance to the ambient temperature [2].
Once the fuse reaches its melting temperature it transitions into an open circuit. A first modeling approach for this transitioning process exists in [8]; a series RC circuit is proposed to approximate the arcing behavior. This circuit is added to the current path once the melting temperature is reached. As an improvement, the resistor is switched between two values, resulting in the model structure shown in Figure 3. Specifically, R_m represents the fuse's resistance during the short period of melting and R_a represents the resistance of the arc. The parameters of the model can be identified using a test measurement. Exemplary, the determined model parameters for a 15 A ATO fuse are C = 100 µF, R_m = 0,68 Ω, R_a = 0,3 Ω and (t_{arc} - t_{melt}) = 30 ns.

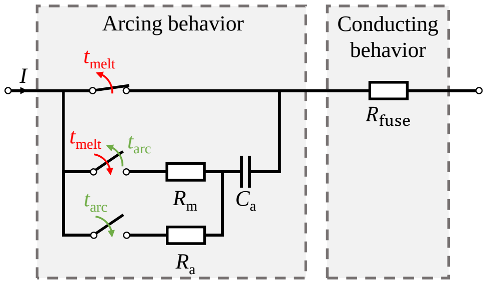

Figure 3: Electrical circuit of melting fuse model. Consideration of conducting and arcing behavior

2.2.7 Electronic Fuse

Electronic fuses (eFuses) will play an integral role in tomorrow's automotive architectures and might progressively replace conventional melting fuses and electromechanical relays [9]. Therefore, correct modeling of the switching behavior of smart fuses is important.
eFuses consist of a power transistor, usually a MOSFET. Established transistor models can be used here. However, additional circuitry of the fuse can affect the switching behavior and needs to be considered too. This may include protection elements like transient-voltage-suppression (TVS) diodes that limit the voltage across the fuse's contacts or the voltage against ground. Furthermore, the fuses are typically controlled by a microcontroller with a significant input capacity to stabilize its supply voltage. Figure 4 shows a possible equivalent model of an eFuse. However, details of the additional circuitry as well as switching slopes of the MOSFET may differ for specific fuses and depending on the manufacturer.
In this contribution, an Infineon BTS50010-1TAD eFuse is used as a reference [10]. This eFuse limits the voltage from drain to ground to 28 V using a TVS diode; the drain-source voltage is actively limited to about 35 V. The stabilizing capacity against ground

is 100 µF. The switching process of this fuse takes about 100 µs. A MOSFET basic model, based on Shichman and Hodges [11], is used for the power transistor.

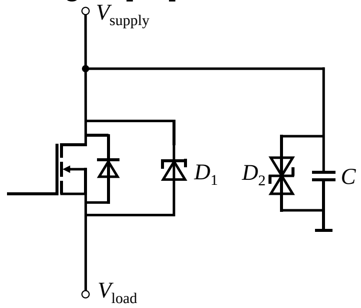

Figure 4: Electronic fuse with MOSFET and additional elements for protection and voltage stabilization

3 Investigated Topology

In this section, a specific power supply topology is defined. Based on this topology, a validation of the simulation models and further simulative investigations shall be performed in the upcoming chapters. The investigated topology is chosen to be a 12V/48V bus topology with power distribution units using electronic fuses and is depicted in Figure 5. With its redundant supply it may be a possible basis for a highly reliable power supply system; the optimization of the protection and fusing concepts regarding this aspect are, however, not subject of this contribution.
The topology consists of three PDUs that are each connected from both sides of the bus structure. The bus wires have a cross section of 16 mm² of varying lengths. For the considered loads a generic RC model is used (refer to section 4.5). Loads 1, 2 and 4 might represent a combination of several different loads connected to their respective PDU. Load 3 represents an additional load at whose location an exemplary short circuit fault shall be examined in the next sections. The wires connecting the loads to the PDUs are equally chosen to have a cross section of 2,5 mm².

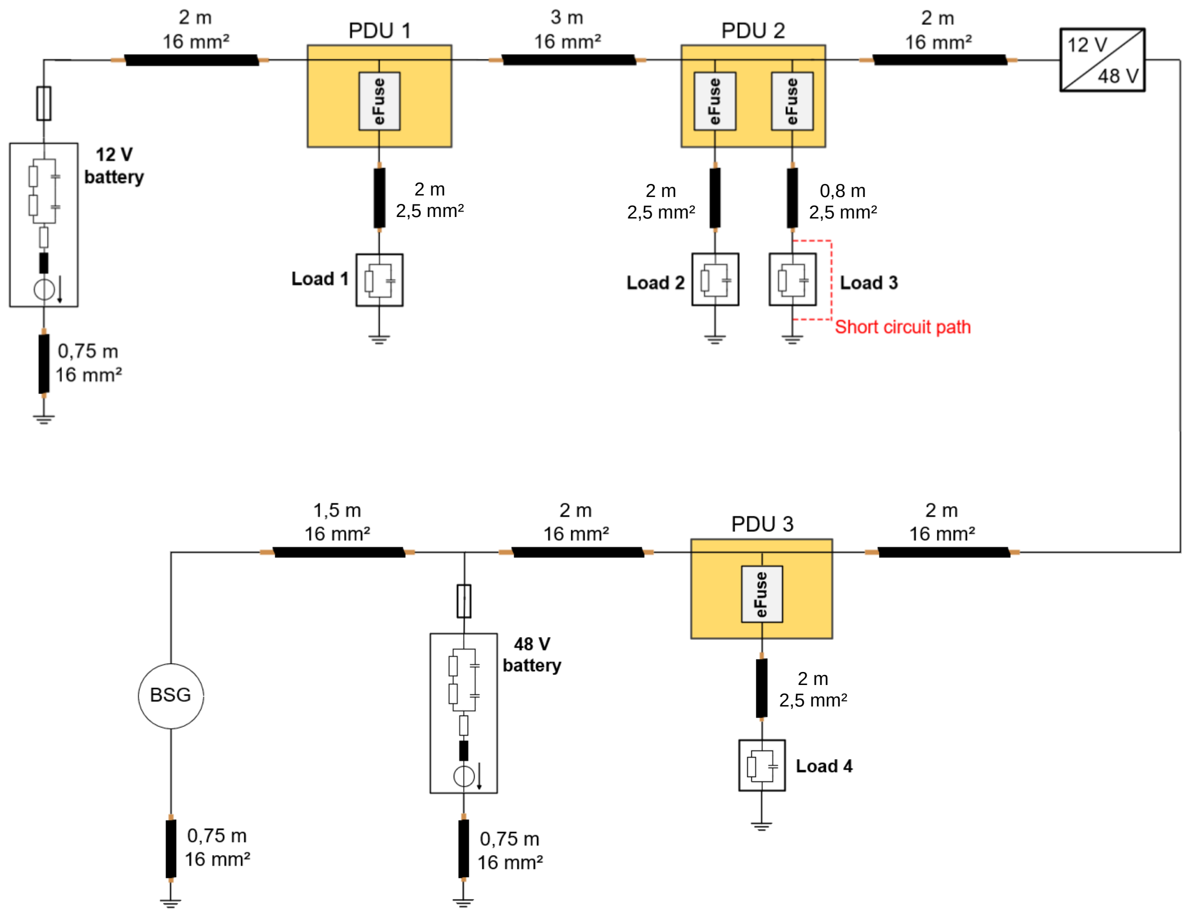

Figure 5: Investigated 12V/48V bus topology

4 Experimental Validation

Before using the presented modeling approaches for simulative investigations, a validation of the models is performed. To do so, a laboratory setup of the 12 V subsystem of the topology, as depicted in Figure 5, is built. A photo of the realized setup can be seen in Figure 6. As a validation scenario, a short circuit fault occurring at load 3 is considered, practically realized by switching the short circuit path (red dashed line in Figure 5) using a high current relay. The DC-DC converter is assumed to be turned off in this scenario.
The load parameters chosen for this measurement are depicted in Table 1. A lead-acid 12 V battery with a capacity of 44 Ah is used. The relevant fuse that is supposed to be triggered in this scenario is the one protecting the wire to the short-circuited load 3. Two parallel Infineon BTS50010-1TAD eFuses are used for this task, because this fuse has a self-protection mechanism that automatically switches the fuse off at about 200 A. As the short circuit current in this scenario is expected to exceed 200 A, a parallel operation of two fuses is used. The algorithm that defines the switching behavior simply checks for a current threshold; if the fuse current exceeds 15 A, the fuse switches off after 2 ms. Since no other fuses are triggered in this scenario, PDU 1 is realized only by the stabilizing capacitor to ground of 100 µF in reference to the BTS50010-1TAD at PDU 2.

An HDO6104A oscilloscope by Teledyne LeCroy is used to measure the voltages at the non-faulty loads 1 and 2 during the described scenario. Additionally, the current of the short circuit path is measured by a Tektronix TCP404XL current probe.

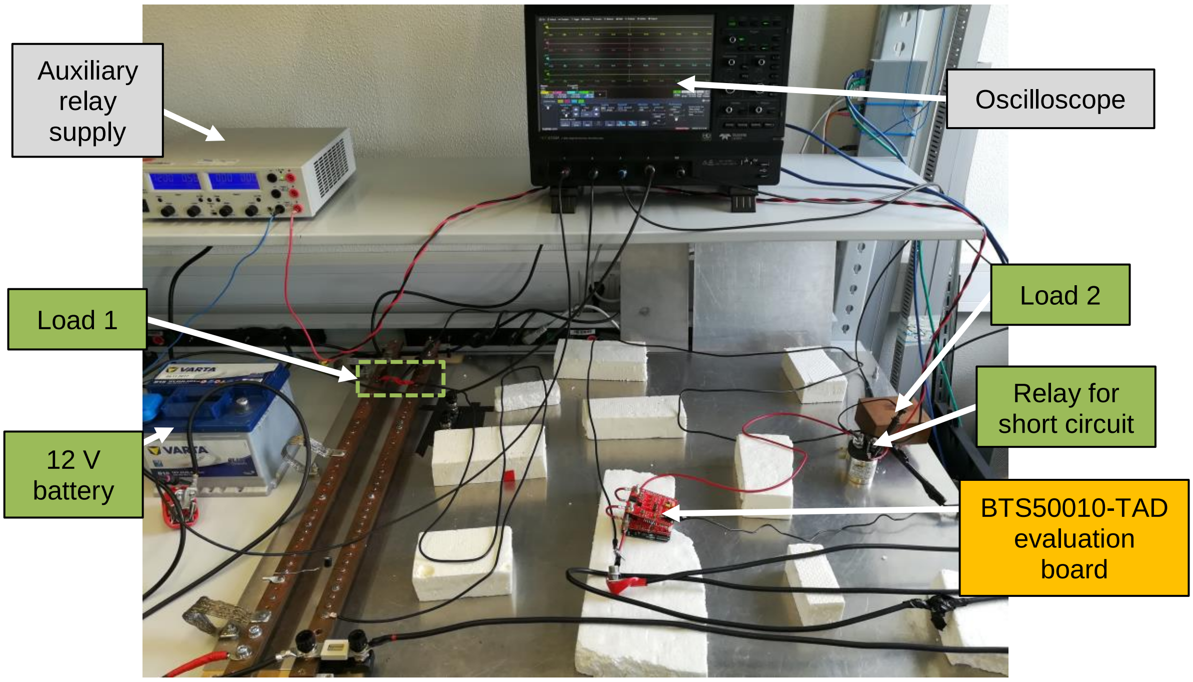

Figure 6: Laboratory setup for validation measurement

The measurement results are depicted in Figure 7. At $t = 0$, the relay switches on. The short circuit current starts to rise until it reaches its peak of about 320 A. The electronic fuse detects the overcurrent and switches off, resulting in the current to fall to 0 A within about 80 µs starting at $t = 1$ ms. Note, that the short circuit current is already non-zero before $t = 0$ due to the bouncing of the relay that happens before fully conducting and last about 1 ms. This process is not further discussed, as it is specific to the practical fault injection method. The voltages of loads 1 and 2 both show a similar behavior. The rising short circuit current slope leads to a voltage undershoot down to 6.8 V at load 1 and 2.8 V at load 2, caused by the wire inductances. After this transient the voltage stays at about 7.3 V (load 1) and 5.7 V (load 2) because of the additional voltage drop across the wire resistances. During the switching process of the fuse both loads experience a significant transient overvoltage (up to about 23 V and 34 V, respectively), again caused by the wire inductances. The transient pulses at load 2 are more significant than those at load 1, because the supply line to PDU 2 is longer, thus having more inductance.
This scenario is now modeled in MATLAB/Simscape using the modeling approach presented in the previous chapters. Open circuit voltage and internal resistance of the battery have been determined to be V_{OCV} = 13.4 V and R_{in} = 16 mΩ. In addition to the impedances of the wires itself, transition resistances of the wire connectors and resistance of the relay need to be considered in the simulation. In total these add up to 15 mΩ in the short circuit path. As there is no relay bounding considered in the simulation, the trigger time of the eFuse model has been reduced to 0.74 ms to allow a better comparison of the resulting waveforms.

Load parameters		
Load 1 - $R_{\mathrm{load},1} = 250\ \Omega$ - *No capacitor*	Load 2 - $R_{\mathrm{load},2} = 4\ \Omega$ - $C_{\mathrm{load},2} = 47\ \mu\mathrm{F}$ - $R_{\mathrm{ESR,load},2} = 1\Omega$	Load 3 - $R_{\mathrm{load},3} = 10\ \mathrm{k}\Omega$ - *No capacitor*

Table 1: Load parameters of the validation scenario

The resulting simulated load voltages and short circuit current are shown as dashed lines in Figure 7. As can be seen the simulation offers a very good representation of the system's transient fault behavior. The simulated transient voltage peaks deviate less than 1 V from the measurements. The width of the voltage pulse during fuse switching is slightly larger in the simulation. This could be due to inaccurate approximation of the wire inductances, frequency-dependent capacitances, or non-optimal modeling of the fuse's transistor. Overall, the results show that the proposed models are suitable to further investigate power supply systems within the simulation.

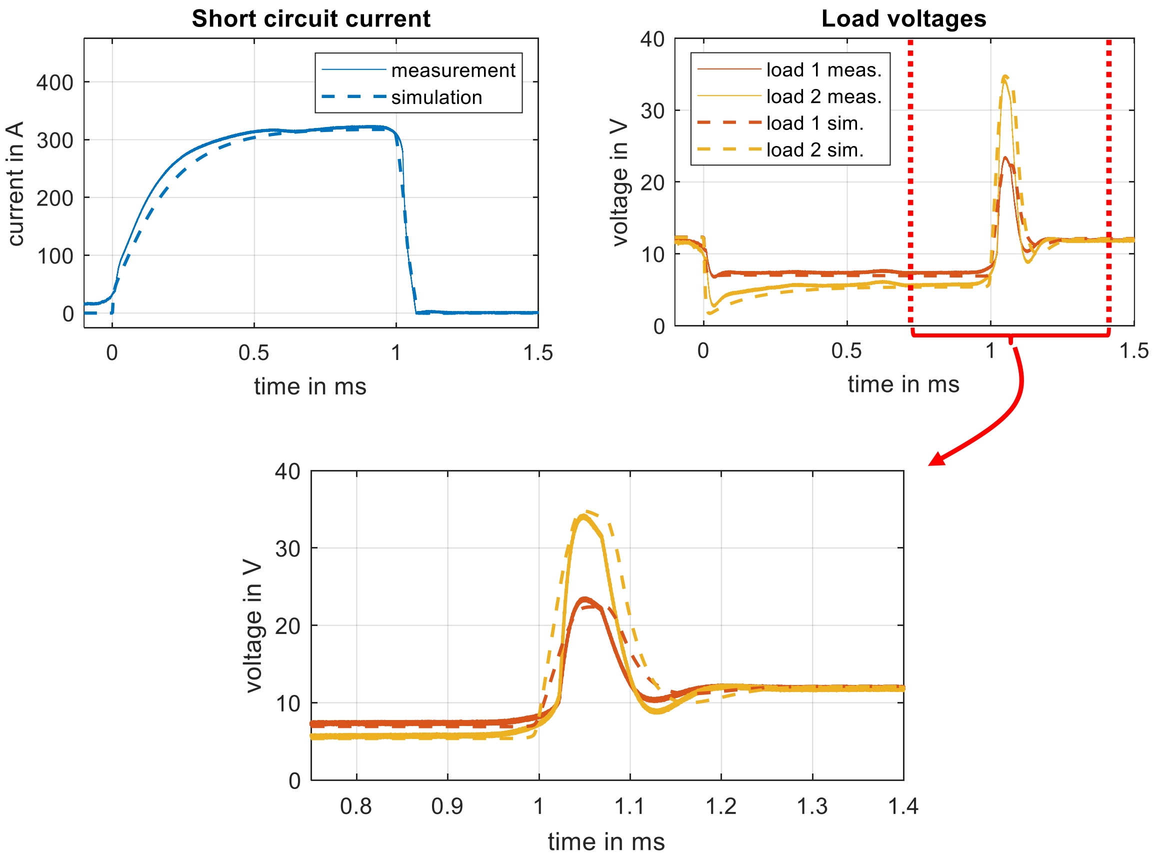

Figure 7: Validation measurements and simulation results of the short circuit scenario. Short circuit current (top left), load voltages (top right) and zoom on voltages during fuse tripping (bottom)

5 Simulative Investigations of Transient Scenarios

With the validated models, comprehensive investigations of power supply systems are possible. This includes consideration of transient voltage stability and fail-operational

performance in early stages of development without the need of expensive and impractical physical prototyping.
In this section, three exemplary aspects of the introduced topology are to be investigated simulatively, i.e., topology changes, parameter variations and a comparison between electronic and melting fuses.

5.1 Introduction of 48 V Level

First, the 12 V subsystem used in the validation scenario is extended by an 48 V branch according to Figure 5. Therefore, the DC-DC converter is now assumed to be active in buck mode, realizing a redundant supply for the 12 V components. To analyze the impact of this extension the short circuit fault at load 3 is now simulated with the activated converter. The assumed converter model doesn't consider control dynamics and has an input and output capacitance of 1 mF each, maximum output current of 200 A, and an output voltage of 14 V. The 48 V battery uses the same parameter as the 12 V battery, except V_{OCV} = 48 V. The generator has an output voltage of 50 V and a control time constant of 100 ms.
The resulting short circuit current and voltage at load 2 are depicted in Figure 8 in comparison to the validation scenario without 48 V subsystem. As can be seen, with additional supply from the converter, the short circuit current is able to rise as high as about 440 A. However, the switching of this higher current by the fuse doesn't produce a higher voltage peak at the nearby loads. This is due to the built-in overvoltage protection that limits the transistor's drain-source voltage to 35 V. The voltage of load 2 only differs before and after the transient peak; because of the additional 14 V supply it is about 2 V larger compared to the case without converter. The voltage at load 1 shows the same general behavior.

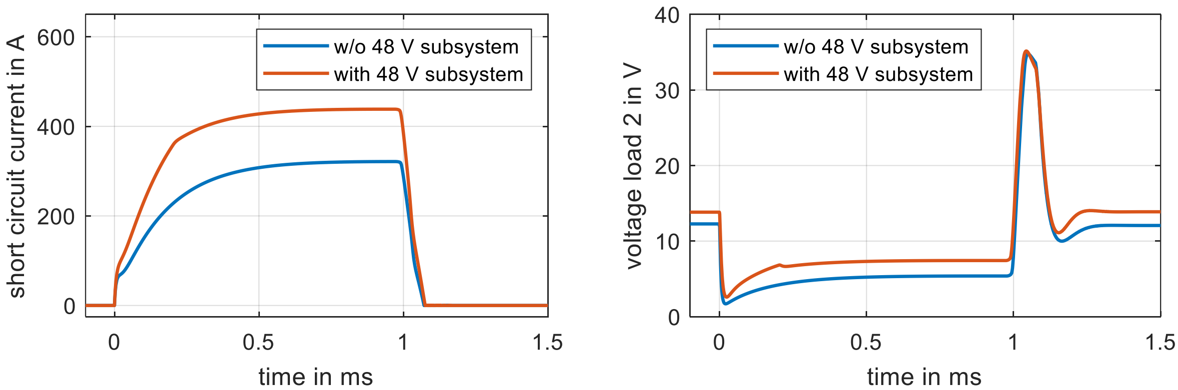

Figure 8: Simulation of the topology from Figure 5 with and without activated 48 V subsystem during a short circuit at load 3. Short circuit current (left) and voltage at load 2 (right)

5.2 Parameter Variation

Parameter studies can be a tool to examine within the simulation, how safety-critical transient events such as over-voltages might be prevented. As an example, the influence of the capacitor of load 2 on its voltage peak during the discussed short circuit fault is investigated. To do so, the load capacitance and the capacitor's ESR are varied

over several magnitudes and the short circuit at load 3 is simulated (with 48 V subsystem). The maximum value of the voltage peak during fuse switching is evaluated and depicted in Figure 9 as a surface plot.
The parameter variation shows that small capacitances of 10 µF or less have no significant impact on the voltage peak of load 2, which is about 35 V. Counter-intuitively, an increase of the capacitance to about 100 µF also increases the peak load voltage. For small ESR values (up to about 20 mΩ), the voltage now reaches more than 45 V. This can be explained by a resonance behavior between the load capacitance and the wire inductances. A high ESR attenuates this resonance and decreases the load voltage significantly; above 0,1 Ω the voltage peak drops below 40 V. With an increase of capacitance to more than 1 mF the voltage peak drops far below the initial 35 V at small capacitances. High capacitances basically short the current pulse caused by the wire inductances and prevent a rise in load voltage. Now a high ESR is not beneficial, as it increases the capacitors impedance and counteracts this effect.

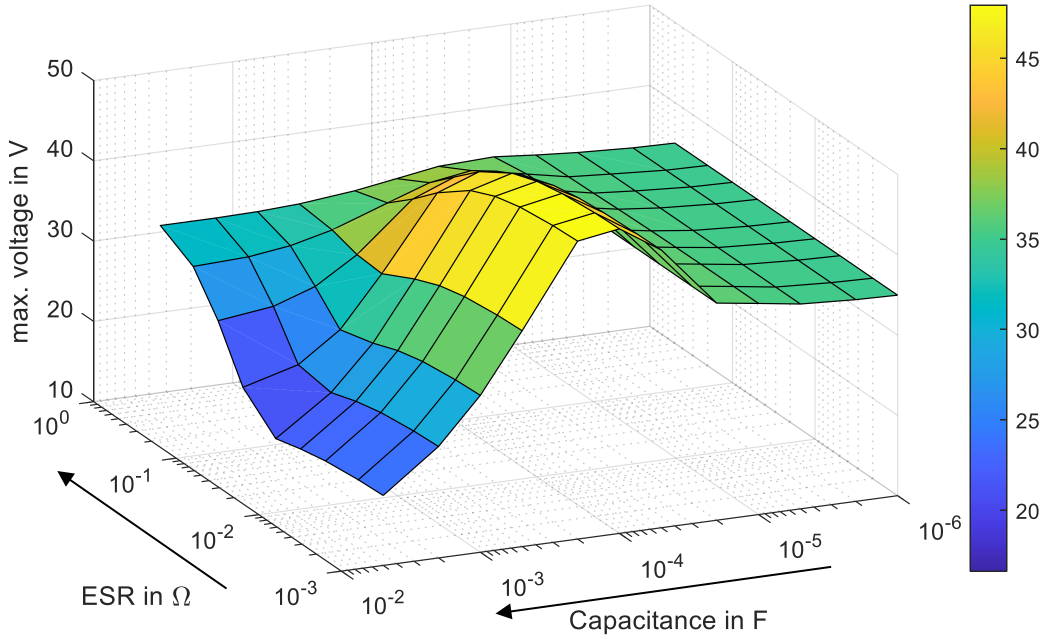

Figure 9: Parameter variation of load 2. Simulated peak voltage at load 2 for different values of its capacitor's ESR and capacitance

5.3 Comparison of Electronic and Melting Fuse

As today's vehicles still use conventional melting fuses, it is of interest how their transient behavior influences the remaining supply system and how this influence differs from electronic fuses. Therefore, the investigated short circuit scenario is also simulated using a 15 A melting fuse instead of the eFuse. An active 48 V subsystem and default load parameters from Table 1 are assumed. Figure 10 shows the simulation results in comparison to the ones using the BTS50010-1TAD eFuse.
The resistance of the melting fuse increases with temperature and is generally higher than the eFuse's $R_{DS(on)}$, thus the maximum short circuit current is lower. However, the resulting voltage peak at load 2 reaches 51 V and is therefore higher than when using the eFuse. This can be explained by the faster switching process of the melting fuse that leads to a greater current derivative di/dt, causing higher voltages across the wire

inductances. Also, the stabilizing capacitors used by the eFuses (in this case 100 µF) are not present when using conventional melting fuses.

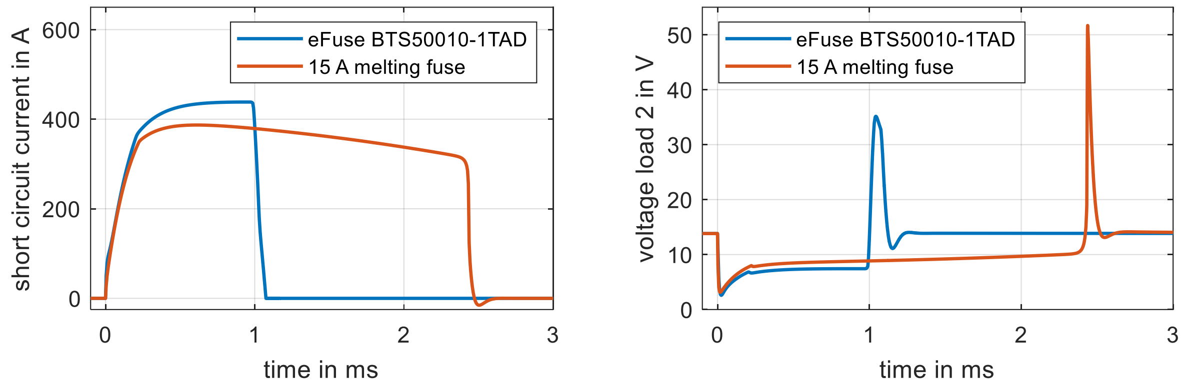

Figure 10: Simulation of short circuit at load 3 protected by BTS50010-1TAD eFuse vs. 15 A melting fuse. Short circuit current (left) and voltage at load 2 (right)

Analog to section 7.2, the parameter variation of the capacitor of load 2 is also performed using the melting fuse (Figure 11). A capacitance of about 100 µF doesn't cause the same resonance as previously observed with the eFuse. Instead, a higher capacitance is generally beneficial to mitigate the over-voltage. This is plausible, as the absence of the eFuse's stabilizing capacitors changed the resonant behavior of the overall system.

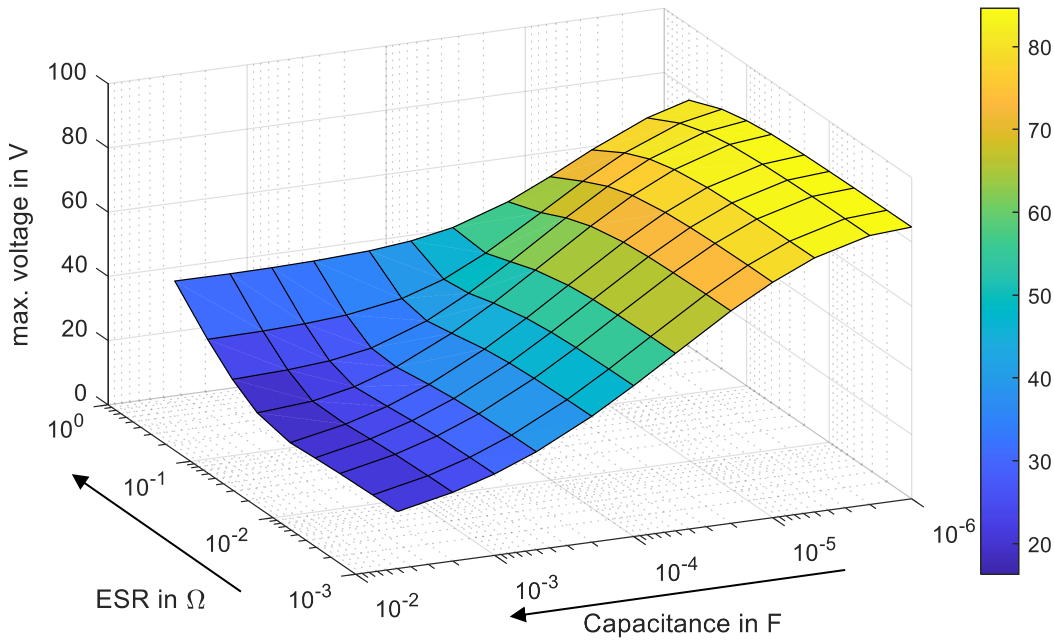

Figure 11: Parameter variation of load 2 with melting fuse. Simulated peak voltage at load 2 for different values of its capacitor's ESR and capacitance

6 Conclusion

In this contribution, the transient voltage stability of automotive power supply systems has been analyzed. Simulation models have been presented that focus on transient processes and switching events. A validation measurement using a laboratory setup confirmed the suitability of the proposed modeling approach. Exemplary simulative investigations illustrated the possibilities that simulations offer for developing highly-reliable power supply systems. Specifically, the influence of load capacitances and fuse type (conventional vs. electronic fuse) on transient over-voltages have been evaluated. Future work will focus on methods for finding the most critical configurations in extended power supply systems.

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