Models of Automotive Power Supply Components for the Transient Analysis of Switching Events and Faults

M.Sc. Michael Gerten, TU Dortmund University, On-board Systems Lab, Dortmund, Germany
M.Sc. Marvin Rübartsch, TU Dortmund University, On-board Systems Lab, Dortmund, Germany
Prof. Dr.-Ing. Stephan Frei, TU Dortmund University, On-board Systems Lab, Dortmund, Germany

Abstract

Highly automated driving increases the requirements on the transient voltage stability of automotive power systems. Simulations are necessary to analyze voltage stability in early stages of development. In this paper, necessary extensions of existing simulation approaches are discussed to investigate the transient effects of switching operations and electrical faults on the voltage stability of other components. First, the models of the relevant faults and power supply components are presented. Finally, a validation of the developed models is performed using laboratory measurements of an exemplary power supply topology.

1 Introduction

The requirements on vehicle's functional safety will increase due to 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 that 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-voltages 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 realistically 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. On the other hand, there has to be a trade-off regarding computational complexity. Simulations need to be fast enough to allow investigations of a variety of complex scenarios in an acceptable time, including different topologies, fault types and parameter sets.

This paper analyzes critical aspects and possibilities of the transient simulation of automotive power supply systems. First, section 2 clarifies the challenges of accurate transient simulations. The relevant fault and component models are described in sections 3 and 4, respectively, and enhancements to existing modeling approaches are discussed. Based on an exemplary power supply system introduced in section 5, an experimental validation of the presented models is performed in section 6. The paper closes with a conclusion and an outlook.

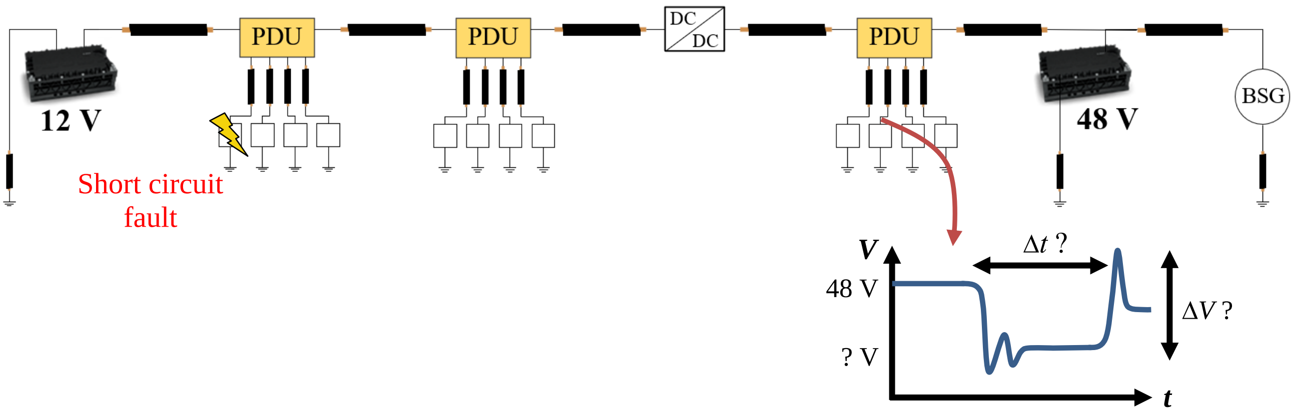

Figure 1: Generalized supply system with bus topology utilizing power distribution units (yellow) and exemplary depiction of a short circuit fault

2 Transient Effects of Switching Events

If the transient consequences of switching events and electrical faults are to be analyzed in a simulation, it is particularly important that these events are modeled realistically. Otherwise, the simulation may only yield accurate results in steady-state scenarios, while showing significant deviation during the transition periods between these states. In existing model libraries, e.g. [2] and [3], transient events are modeled as discrete steps. For example, a tripping fuse is realized as a jump in the fuse's impedance to its open circuit value. Likewise, during a short circuit fault, the resistance at the fault location jumps from its high-ohmic nominal value to a low-ohmic value within one simulation timestep. These discrete steps can lead to high current slopes, which in turn would result in high voltages caused by the inductances of the system. **Figure 2** demonstrates this behavior in a simple circuit of two parallel resistive loads. At time $t = 0$, the 1 Ω load gets disconnected, e.g., due to a faulty opening of the connector. If this switching event is simulated as an instantaneous jump in resistance, the whole inductor current has to flow through the 150 Ω load, causing a voltage peak of 1800 V. However, this behavior is far from realistic, as the laboratory measurement of the same circuit during the disconnection of a connector shows. Here, the voltage peak is significantly lower and lasts significantly longer. Thus, to investigate the effects of transient events, a more accurate modeling of these events is necessary, including possible transient effects like arcing, melting, and switching slopes of transistors.

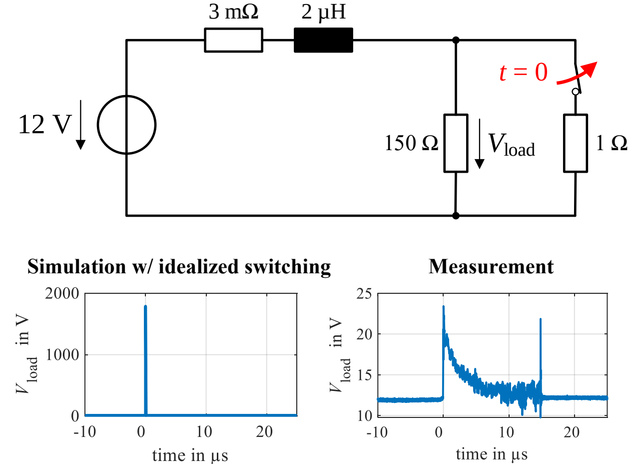

Figure 2: Switching behavior in an inductive circuit with two loads. Simulated load voltage using

3 Fault Modeling

In complex supply systems many different faults can occur at various locations. As seen in the previous section, transient faults can have a significant impact on the voltage stability. This section focuses on the realistic modeling of these transient faults in the wiring system, i.e., short circuit and open circuit faults. Gradual faults, e.g., increasing contact resistance, and internal component faults are not within the scope of this contribution.

3.1 Short Circuit

A short circuit can occur between a supply line and ground potential or between supply lines of different voltage levels, e.g., 12 V and 48 V. Since the short circuit current is only limited by the low resistances of the wiring and the maximum current capabilities of the energy sources, it poses a critical scenario.

The transitioning process of two closing contacts with different potential is described in [7]. Usually, an electric arc forms just before a conductive connection is established. However, arcing times in this case are in the range of microseconds and might be neglectable. This is confirmed by a current measurement of a supply wire (resistance 40 mΩ; inductivity 3 µH) that is shorted to ground. As depicted in **Figure 3**, the waveform of the increasing short circuit current is primarily determined by the L/R time constant of the wiring. Hence, a short circuit fault can be accurately modeled as a discrete step of the resistance without the consideration of arcing.

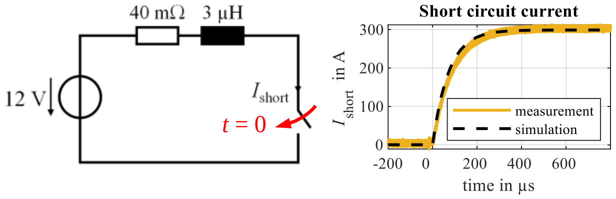

Figure 3: Short circuit of a supply wire to ground. Simulated short circuit current using a resistance jump vs. measurement

3.2 Open Circuit

In contrast to a short circuit, an open circuit fault occurs if a conductive connection is suddenly interrupted, e.g., due to a breaking wire or a loosening connector. To accurately model these faults, the physical behavior of opening contacts needs to be considered. As elaborated in [7], once a metallic connection is interrupted an electric arc is initiated even for currents as low as 1 A. To evaluate the effect of the fault on the remaining supply system it is important to approximate the *V-I* characteristics of this arc, as the change in current determines the voltage induced by the wiring inductances.

In general, the arc model can be realized as a voltage source that represents the voltage across the opening contacts. In 48 V or HV supply systems stable arcs can form, whose voltage depends nonlinearly on their current and the distance of the contacts [8].

In 12 V supply systems the conditions for a stable arc are usually not met, as a minimum arc voltage of about 15 V is needed to sustain an arc [8]. **Figure 4** shows the voltage across and the current through a connector during an exemplary open circuit fault in a 12 V system. Almost immediately after the fault occurs at $t = 0$ µs, the arc is initiated with its minimum arcing voltage of 15 V. The current starts to fall until it reaches 0 A after about 110 µs, thus extinguishing the arc.

Due to this behavior, in 12 V systems the arc can be approximated by a constant voltage source representing the minimum arcing voltage, that transitions to an open circuit once the current reaches 0 A. As is depicted in Figure 4, this approach yields a good reproduction of the measured current waveform, which is essential to the accurate modeling of the wiring inductances' behavior. Therefore, more sophisticated arcing models are not necessary in this case.

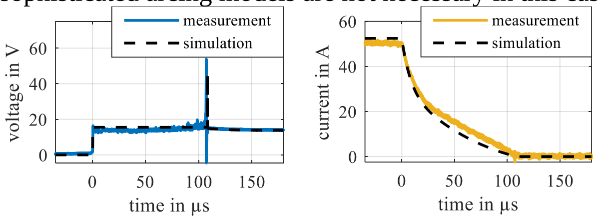

Figure 4: Voltage and current of an exemplary open circuit in a 12 V supply system. Measurement vs. simulation

4 Component Modeling

In this section, existing modeling approaches are evaluated and enhancements are proposed to improve their transient behavior. As this contribution focuses on the simulation of switching events and fast electrical faults, events of larger timescales like aging or dynamic driving cycles are not considered. Implementation of the presented models is performed in MATLAB/Simscape.

4.1 Battery

A lot of research has been done on modeling the electrical behavior of batteries, e.g. [9] and [10]. This includes simple approaches consisting of a voltage source with internal resistance to more sophisticated ones incorporating nonlinear behavior and variable state of charge (SoC) and state of health (SoH). As only short simulation times are relevant in this contribution, an operating point with constant SoC and SoH is assumed here.

The model structure used in this paper is depicted in **Figure 5**. The static behavior is determined by the open-circuit voltage V_{OCV} and the total internal resistance $R_{\mathrm{in}} = R_1 + R_2 + R_3$. To approximate the dynamics of internal chemical processes, two RC circuits are used. Typical values for an 80 Ah lead-acid battery, according to [5], are $R_1 = R_2 = 3\ \mathrm{m\Omega}$, $R_3 = 10\ \mathrm{m\Omega}$, $C_1 = 1$ F and $C_2 = 300$ F. For improvement of the transient behavior, the batterie's inductance is also considered in the model, a reference value being $L = 50$ nH [9]. Parameters for specific battery types and states can be acquired through measurements.

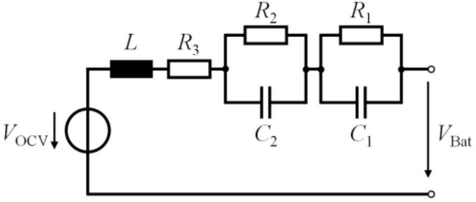

Figure 5: Schematic of the battery model

4.2 Generator

A typical automotive generator is a three-phase, self-excited synchronous machine with an integrated rectifier. A controller adjusts the excitation current to control the output voltage according to the desired reference value. The maximum available output current depends on the rotational frequency and the current rating of the generator. The implementation of the generator model used in this contribution is based on [2]. An important aspect of the generator's dynamic behavior is the time constant due to the inductance of its windings. It can be as high as 100 ms [11] and limits the rate at which the generator current can change. This can lead to high and long over-voltages during switching events.

4.3 Wiring

In general, wires of a given length l can be described by the equivalent circuit depicted in **Figure 6** [12]. As further analyzed in [4], the parallel capacitances and conductances are very small. It has been shown they have no influence on the investigated events in this paper and therefore a resistive-inductive wire model is used. The specific inductance of a wire over a conductive plane (e.g. chassis) can be analytically calculated and depends on the wire's cross section and its distance from the plane. As an approximate value $L' = 1\ \mu\mathrm{H/m}$ is used. [4]

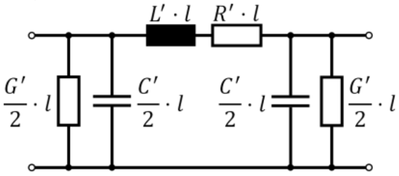

Figure 6: General equivalent circuit of a wire

4.4 DC-DC converter

In supply systems with multiple voltage levels, DC-DC converters are responsible for the power flow between these levels. Depending on the current power consumption and generation they can operate in either buck or boost mode. As shown in [3], 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 and/or inductors influence the transient behavior [13].

4.5 Loads

Modern vehicles include a variety of electronic control units (ECUs) and other electric loads. The 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]. Purely resistive models can be used to model, e.g., window heaters.

4.6 Switching Components

Besides unintentional faults, there are components whose intentional behavior includes switching of individual loads or subsystems, i.e., melting fuses, relays, or semiconductor switches. These switching events may also cause critical voltage pulses and affect other components, therefore accurate modeling of these components is important.

4.6.1 Melting Fuses

Melting fuses still play an important role in today's automotive power supply architectures. Their function 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. While this transition process is important for an accurate transient simulation, it is not considered in the mentioned existing model libraries. A first modeling approach exists in [14]; 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 7**. 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. **Figure 8** shows the measured and simulated current and voltage waveforms of an exemplary melting process of a 15 A fuse. The sudden increase in resistance due to the melting at $t = 0$ leads to a voltage spike caused by the circuit's inductance. The current approaches zero after about 30 µs of arcing. The determined model parameters in this case are $C = 100$ µF, $R_m = 0{,}68\ \Omega$, $R_a = 0{,}3\ \Omega$ and $(t_{arc} - t_{melt}) = 30$ ns.

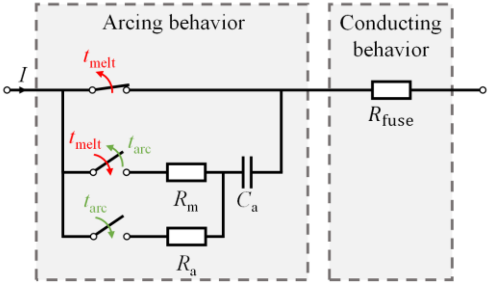

Figure 7: Electrical circuit of melting fuse model. Consideration of conducting and arcing behavior

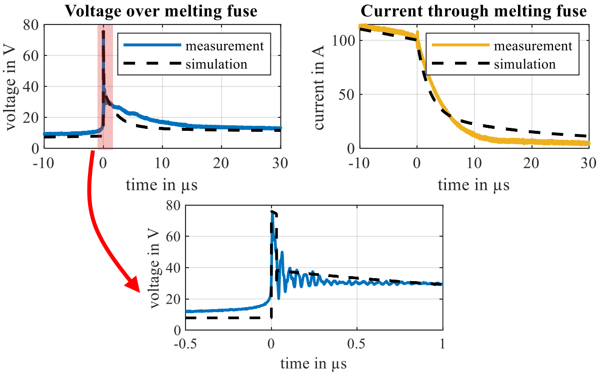

Figure 8: Voltage and current of a 15 A melting fuse during exemplary melting process.

4.6.2 Relays

Electromechanical relays are commonly used to actively switch loads. As the switching currents may be significant, they pose a source for transient voltage pulses. Inside a relay electrical contacts are either closing or opening, leading to the same arcing effects already explained for short and open circuit faults (refer to section 3). Relays switching can therefore be modeled analogously to short circuit faults (closing relay) and open circuit faults (opening relay). To consider bouncing of the contacts during closing of the relay, several individual closing and opening operations can be simulated. For bridge-type relays with more than one point of contact, an arc can form at every contact which needs to be considered in the simulation.

4.6.3 Electronic fuses

Electronic fuses (eFuses), also called smart fuses, will play an integral role in tomorrow's automotive architectures and will progressively replace conventional melting fuses and electromechanical relays [16]. Beyond thermal wire protection, eFuses enable additional features, e.g., active switching of loads or subsystems and advanced monitoring and diagnosis functions. Therefore, correct modeling of the switching behavior of smart fuses is important.

eFuses consist of a power transistor, usually a MOSFET. Since the switching of a MOSFET is a controlled and well understood process, it can be modeled using existing transistor models. 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 fuse is typically controlled by a microcontroller with a significant input capacity to stabilize its supply voltage. **Figure 9** 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.

An exemplary switching process of an Infineon BTS50010-1TAD eFuse evaluation board [16] is depicted in **Figure 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. As can be seen, a simulation using Simulink/Simscape's MOSFET model (based on Shichman and Hodges [18]) offers a good reproduction of the measured behavior of this fuse.

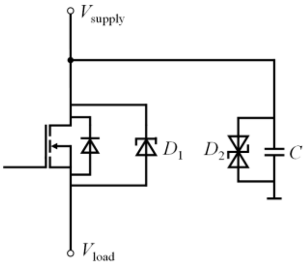

Figure 9: Electronic fuse with MOSFET and additional elements for protection and voltage stabilization

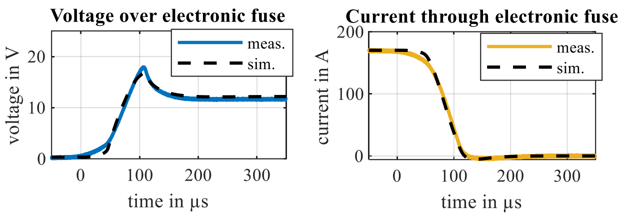

Figure 10: Exemplary voltage and current waveforms of an electronic fuse (Infineon BTS50010-1TAD) switching a short circuit current. Measurement vs. simulation

5 Investigated Topology

In this section a specific power supply topology is defined. Based on this topology, a validation of the simulation models shall be performed in the upcoming chapter. The investigated topology is chosen to be a 12 V bus topology and is depicted in **Figure 11**. With an additional redundant supply (e.g. DC-DC converter) it may be a possible basis for a highly reliable power supply system.

The topology consists of two PDUs using eFuses. 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). While loads 1 & 2 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.

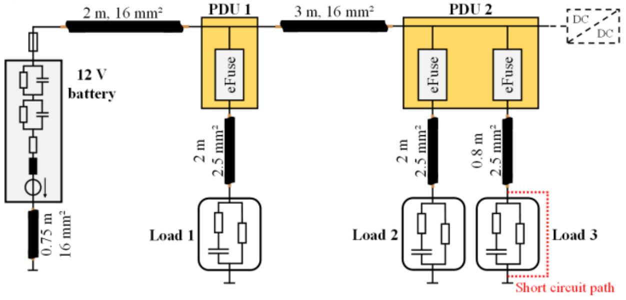

Figure 11: Investigated bus topology

6 Experimental Validation

To examine the suitability for simulating the consequences of transient events in automotive power supply systems, a validation using measurement data is performed. A laboratory setup of the topology depicted in Figure 13 is built. A photo of the realized setup can be seen in **Figure 12**. 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 13) using a high-current relay.

The load parameters chosen for this measurement are depicted in **Table 1**. The used 12 V battery is a Varta 544 402 044 with a capacity of 44 Ah. 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 analogy to 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.

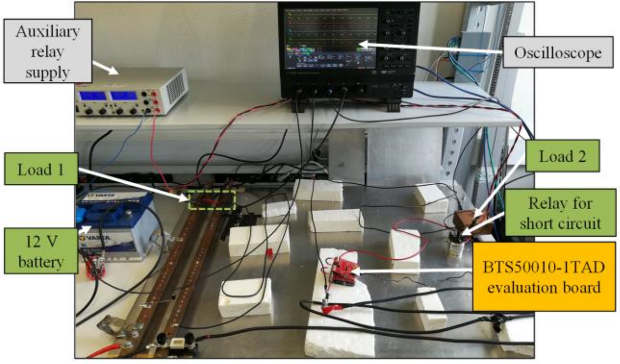

Figure 12: Laboratory setup for validation measurement

Table 1: Load parameters of the validation scenario

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

The measurement results are depicted in **Figure 13**. At $t = 0$, the relay switches on and the short circuit current starts to rise until it reaches its peak of about 320 A. The eFuse 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 there is relay bouncing for about 1 ms prior to $t = 0$ that is not further discussed here. 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; this is caused by the wire inductances and the additional voltage drop across the wire resistances. During the switching process of the fuse both loads experience a significant transient over-voltage (up to about 23 V and 34 V, respectively). The transient pulses at load 2 are larger than those at load 1, because the supply line to PDU 2 is longer, thus having more inductance.

This scenario is now recreated 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 $V_{\text{OCV}} = 13{,}4\ V$ and $R_{\text{in}} = 16\ \text{m}\Omega$. In addition to the wires, transition resistances of the wire connectors and the relay are considered that add up to 15 mΩ in the short circuit path. The trigger time of the eFuse model has been reduced to 0,74 ms to compensate for the relay bouncing in the measurement.

The simulation results are shown as dashed lines in **Figure 13**. As can be seen, the simulation offers a very good representation of the system's transient fault behavior. The transient voltage peaks deviate less than 1 V from each other. The width of the voltage pulse during fuse switching is slightly larger in the simulation. This could be due to non-optimal modeling of the fuse's transistor or frequency-dependent capacitances. Overall, the results show that the proposed models are suitable for further investigations on power supply system's stability.

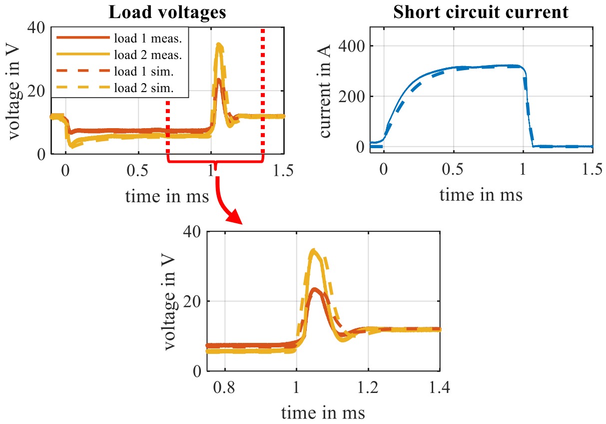

Figure 13: Validation measurement and simulation results of the short circuit scenario. Short circuit current (top right), load voltages (top left) and zoom on voltages during fuse tripping (bottom)

7 Conclusion

In this contribution, models for the transient simulation of automotive power supply systems are presented and discussed. It has been shown that accurate modeling of the switching behavior is necessary to analyze how switching events influence other components of the system. Modeling approaches for common supply system components are proposed. Validation measurements using a laboratory setup confirm the suitability of the presented models.

Future work will focus on optimizing the simulation models to further increase accuracy and efficiency. The models can then be used for a systematic investigation on how switching elements such as eFuses interact with the power supply system and, ultimately, how voltage stability and fail-operational behavior can be achieved in future vehicles.

8 Literature

[1] T. Schmid, S. Schraufstetter, S. Wagner, and D. Hellhake, "A Safety Argumentation for Fail-Operational Automotive Systems in Compliance with ISO 26262," in *2019 4th International Conference on System Reliability and Safety*.

[2] Forschungsvereinigung Automobiltechnik e.V., "Erstellung einer VHDL-AMS Modellbibliothek für die Simulation von Kfz-Systemen: FAT-Schriftenreihe 207," 2006.

[3] Forschungsvereinigung Automobiltechnik e.V., "Simulationsgestützte Analyse und Bewertung der Fehlertoleranz von Kfz-Bordnetzen: FAT-Schriftenreihe 334," 2020.

[4] R. Gehring, *Beitrag zur Untersuchung und Erhöhung der Spannungsstabilität des elektrischen Energiebordnetzes im Kraftfahrzeug*. Dissertation, Technische Universität München, 2013.

[5] M. S. Bechteler, C. M. Schessl, and T. F. Bechteler, "Electrical Power Net Systems in Cars—Impedance Modeling and Measurement," *IEEE Trans. Veh. Technol.*, vol. 59, no. 3, pp. 1148–1155, 2010.

[6] F. Ruf, *Auslegung und Topologieoptimierung von spannungsstabilen Energiebordnetzen*. Dissertation, Technische Universität München, 2014.

[7] P. G. Slade, *Electrical Contacts: Principles and Applications, Second Edition,* 2nd ed. Boca Raton: CRC Press, 2013.

[8] M. Kiffmeier, *Modellbasierte Analyse und Diagnose von Lichtbogenfehlern in 48 V Kfz-Bordnetzen*. Dissertation, Technische Universität Dortmund, 2021.

[9] H. Dai, B. Jiang, and X. Wei, "Impedance Characterization and Modeling of Lithium-Ion Batteries Considering the Internal Temperature Gradient," *Energies*, vol. 11, no. 1, 2018.

[10] P. Keil and A. Jossen, "Aufbau und Parametrierung von Batteriemodellen," in *19. DESIGN&ELEKTRONIK-Entwicklerforum Batterien & Ladekonzepte*, München, 2012.

[11] D. J. Perreault and V. Caliskan, "Automotive Power Generation and Control," *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 618–630, 2004.

[12] W. Plaßmann and D. Schulz, *Handbuch Elektrotechnik*. Wiesbaden: Springer Fachmedien Wiesbaden, 2013.

[13] M. Baumann, C. Weissinger, and H.-G. Herzog, "System Identification and Modeling of an Automotive Bidirectional DC/DC Converter," in *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Hanoi, Vietnam, 2019.

[14] T. Tanaka, H. Kawaguchi, T. Terao, T. Babasaki, and M. Yamasaki, "Modeling of fuses for DC power supply systems including arcing time analysis," in *Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International*, Rome, Italy, 2007.

[15] K. Bo, X. Zhou, and G. Zhai, "Simulation of Arc Dwelling Behavior During Bridge-Type Contacts Opening Process for High-Power Relay," *IEEE Trans. Compon., Packag. Manufact. Technol.*, vol. 8, no. 6, pp. 975–981, 2018.

[16] S. Önal and S. Frei, "A model-based automotive smart fuse approach considering environmental conditions and insulation aging for higher current load limits and short-term overload operations," *IEEE ESARS-ITEC*, Nottingham, 2018.

[17] Infineon Technologies AG, "User Manual High Side Switch Shield with BTS50010-1TAD for Arduino: Revision 1.0," 2017.

[18] H. Shichman and D. A. Hodges, "Modeling and simulation of insulated-gate field-effect transistor switching circuits," *IEEE J. Solid-State Circuits*, vol. 3, no. 3, pp. 285–289, 1968.