2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)

Fast Evaluation of the Transient Voltage Stability of Highly Reliable Automotive Power Supply Systems

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***Abstract*— Future automotive power supply systems must be fail-operational. Therefore, it has to be ensured that safety-relevant components do not experience critical under- or over-voltages even in case of a fault. Besides long-term effects, transient pulses within the system caused by switching events need to be investigated too. While existing simulation models are well suited for evaluating the transient voltage stability, accurate simulations of the supply system tend to be time-consuming because of the required numerical integration of the resulting differential equations. This paper proposes a fast evaluation method for the efficient preselection of relevant fault scenarios. Worst-case assumptions are made to approximate the system's behavior with simple analytical expressions leading to a small linear equation system. The method is applied to an exemplary supply system and shows a reduction in computational time of about 93 % compared to a state-of-the-art circuit simulation program.**

Keywords*—Automotive power supply; transient; voltage stability; switching event; simulation.

I. Introduction

Automated driving requires future vehicles to be fail-operational, which means the operation of safety-relevant components has to be ensured even in case of failures within the power supply system [1]. Even short disturbances of the voltage stability may be critical and need to be prevented. Established development processes are not sufficient anymore and it is necessary to evaluate the voltage stability based on simulations in early development stages. Past research mainly focused on slow events and static consequences of failures on the on-board voltage stability, e.g. [2, 3]. Due to the increasing necessity for a highly reliable power supply, recent works also focused on transients [4, 5]. Faults within the wiring system (i.e., short and open circuits) and resulting switching of conventional or electronic fuses (eFuses) have been identified as one significant source of critical transient over-voltages [6]. Due to the large number of possible configurations and fault scenarios, fast simulations can be beneficial for detecting critical fault scenarios and designing a highly reliable power supply system. The known modeling approaches as presented in, e.g., [6], enable accurate investigations of transients and their propagation within a supply system. However, tools like MathWorks' MATLAB/Simscape can be slow, as the solution of a nonlinear differential-algebraic equation system is necessary [7]. When selecting and optimizing highly reliable power supply topologies, a large number of different fault configurations needs to be investigated. Therefore, faster methods are needed to evaluate the transient voltage stability of supply systems.

This contribution proposes a method that applies an efficient preselection technique to identify relevant wiring fault scenarios. Afterward, only a small number of potentially critical scenarios need to be simulated accurately. The paper is structured as follows: First, transient voltage stability in automotive power supply systems is discussed. After an overview of the proposed evaluation method, the developed preselection process is described in detail. Finally, the method is applied to an exemplary system to demonstrate its efficiency. To show the validity of this method, the results are compared to extensive Simscape simulations.

II. Transient Voltage Stability

When evaluating the transient voltage stability, wiring faults and switching events must be considered. Short circuit faults may result in large currents leading to an undervoltage within the supply system. When the short circuit triggers a fuse, this large current is switched off, potentially resulting in significant voltage peaks induced by the wire inductances. Intentional switching of large loads or open circuit faults may have a similar effect on the overall system. Different criteria for evaluating voltage stability have been proposed, e.g., in [3]. However, these do not focus on short transient pulses. On the other hand, several standards define transient test pulses that automotive on-board components have to tolerate without loss of function, e.g., ISO 7637 [8] or VW 80000 [9]. Based on such standard pulses, voltage-time criteria for evaluation of the transient voltage stability may be derived. However, the method proposed in this contribution is independent of the utilized criteria.

III. Proposed Evaluation Method

The objective of the proposed method is to assess the supply voltage of safety-critical loads for all possible single fault scenarios of the wiring system. Specifically, a short circuit at each system node and a wire break of each wire is investigated. To do so, a two-step preselection process, depicted in Fig. 1, is developed that efficiently separates uncritical fault scenarios from potentially critical ones. The supply system topology that is to be investigated is initially defined in a text-based netlist format, similar to a SPICE netlist. During the preselection process, worst-case assumptions are made that enable a fast approximation of the system's fault behavior. The first stage uses DC circuit simulations and analytical calculations to approximate the resulting load voltages by rectangular functions. In the second stage, transient circuit simulations are performed. Finally, the remaining and potentially critical scenarios are simulated in Simscape with high accuracy and evaluated.

As further analyzed in [4], events that switch off a current always have a finite current slope. This may be due to arcing (e.g. in tripping melting fuses), parasitic capacitances, or the finite switching speed of MOSFETs (eFuses). To accurately simulate the transient effects of those switching processes on the supply system, realistic models are required that may slow down the simulation speed. The central simplification that is used in both preselection stages is the assumption of ideal switching, i.e., an instantaneous jump from low to high resistance. The resulting large current slopes lead to larger voltages induced by the wire inductances. Therefore, transient voltage peaks are overestimated during preselection. However, ideal switching enables analytical approximations and faster transient simulations. These are suitable to identify uncritical scenarios and total failures (complete loss of supply connection) that do not have to be investigated further.

IV. Approximation Using Rectangular Functions

Events like (fuse) switching and wiring faults result in transient voltage and current changes within the supply system. After these distinct transient events, the system state is assumed to return to a static state. To avoid the computational cost of the calculation of a large number of time steps, the system's fault behavior is approximated by a sequence of static states. As depicted in Fig. 2, the worst-case over- and under-voltages that each load experiences are approximated by a set of rectangular functions.

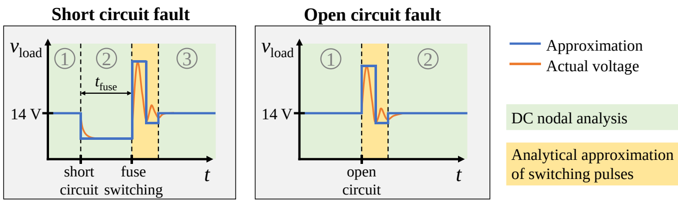

Fig. 2: Exemplary load voltage approximation with rectangular function during short and open circuit fault within the system

A. Static Voltages

As previously mentioned, the investigated system topology is defined in a netlist format. Based on this netlist, a DC simulation can be performed, utilizing the modified nodal analysis (MNA) method [10]. A DC simulation of the nominal netlist provides the nominal static voltages of the system (area 1, Fig. 2). The static state that the system converges to after a wiring fault can also be determined by a DC simulation, as a short or open circuit can be integrated into the netlist easily (area 2, Fig. 2). The static state that results after fuse switching can analogously be simulated by modifying the fuse's state within the netlist (area 3, Fig. 2).

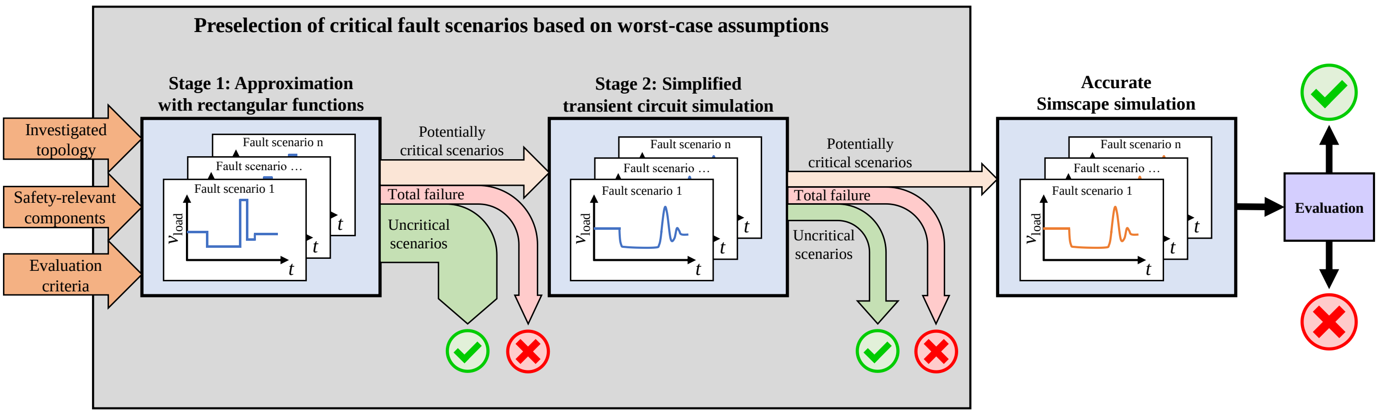

Fig. 1: Schematic overview of proposed evaluation workflow

B. *Fuse Tripping Times*

If a wiring fault results in a fuse current higher than the rated current, then this fuse will trip after a certain time t_{fuse}. This time heavily depends on the specific fuse type, i.e. melting or electronic fuse, and on the implemented algorithm (in case of an eFuse). The tripping time of melting fuses, for example, can be approximated by their characteristic time-current curves. In this contribution, eFuses are assumed that trigger once a fixed current threshold is exceeded for a given time. As a result, the fuse tripping time is known from the parametrization.

C. *Switching Pulses*

The disconnection of currents in branched inductive networks can cause large current slopes. These can trigger oscillations in combination with capacitances and result in large over-voltages at system loads. For a computationally efficient approximation of the system's response to those switching events, analytical methods can be applied. First, a generalized description of an arbitrary system node is defined and is depicted in Fig. 3. This node is assumed to have m different supply paths and n load paths. An additional load path carrying the current I_{sw} is assumed to be switched off.

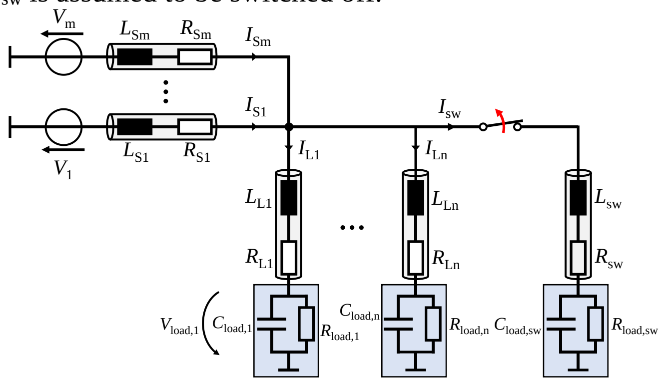

Fig. 3: Generalized system node with m supply paths, n load paths and an additional load path that is switched off

For this generalized topology, the following analytical equations can be derived that describe the relations between the supply (index S) and load (index L) currents directly before and after switching ($I_{\text{S}i}^{\text{pre}}, I_{\text{L}j}^{\text{pre}}$ and $I_{\text{S}i}^{\text{post}}, I_{\text{L}j}^{\text{post}}$, respectively):

$$\begin{aligned}&(L_{\text{S1}} \parallel \cdots \parallel L_{\text{Sm}}) \sum_{i=1}^{m} \left(I_{\text{S}i}^{\text{post}} - I_{\text{S}i}^{\text{pre}}\right)\\ &+(L_{\text{L1}} \parallel \cdots \parallel L_{\text{Ln}}) \sum_{j=1}^{n} \left(I_{\text{L}j}^{\text{post}} - I_{\text{L}j}^{\text{pre}}\right) = 0,\end{aligned} \tag{2}$$

$$\sum_{i=1}^{m} I_{\text{S}i}^{\text{post}} = \sum_{j=1}^{n} I_{\text{L}j}^{\text{post}}, \tag{3}$$

$$\begin{aligned}\Delta I_{\text{S1}} L_{\text{S1}} &= \cdots = \Delta I_{\text{Sm}} L_{\text{Sm}},\\ \Delta I_{\text{L1}} L_{\text{L1}} &= \cdots = \Delta I_{\text{Lm}} L_{\text{Lm}}.\end{aligned} \tag{4}$$

The current differences before and after switching are represented by $\Delta I = I^{\text{post}} - I^{\text{pre}}$. This linear system of $n + m$ independent equations and unknowns can be formulated as a matrix-vector equation (1). As $\boldsymbol{A}$ and $\boldsymbol{b}$ contain only known quantities, i.e., system inductances and currents before switching, the current peaks after switching can be calculated by

$$\boldsymbol{x} = \boldsymbol{A}^{-1}\boldsymbol{b}. \tag{5}$$

Therefore, the load current peaks $I_{\text{L}j}^{\text{post}}$ that result from the switching event are now known. In case of a purely ohmic load, the load voltage peak can be calculated by Ohm's law:

$$V_{\text{load},j} = R_{\text{load},j} \cdot I_{\text{L}j}^{\text{post}} \tag{6}$$

To approximate the peak voltage of an RC load, the following equivalent circuit of the load and its supply path is considered:

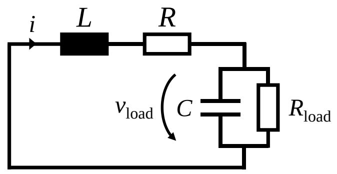

Fig. 4: Equivalent circuit used for analytical calculation of RC load voltage peaks

In this structure, other loads and supply paths are disregarded. As a worst-case assumption, the total supply current is expected to flow into the considered load. Additionally, the wire inductance of the longest supply path and the lowest supply path resistance are assumed to assure that the load voltage peak is not underestimated. This leads to the initial conditions of $i(0) = I_{\text{L1}}^{\text{post}} + \cdots +$

$$\underbrace{\begin{bmatrix} (L_{\text{S1}} \parallel \cdots \parallel L_{\text{Sm}}) & (L_{\text{S1}} \parallel \cdots \parallel L_{\text{Sm}}) & \dots & (L_{\text{L1}} \parallel \cdots \parallel L_{\text{Ln}}) & (L_{\text{L1}} \parallel \cdots \parallel L_{\text{Ln}}) & \dots \\ 1 & 1 & \dots & -1 & -1 & \dots \\ L_{\text{S1}} & -L_{\text{S2}} & \dots & 0 & 0 & \dots \\ 0 & L_{\text{S2}} & \dots & 0 & 0 & \dots \\ \vdots & \vdots & \dots & \vdots & \vdots & \ddots \\ 0 & 0 & \dots & L_{\text{L1}} & -L_{\text{L2}} & \ddots \\ \vdots & \vdots & \dots & \vdots & \vdots & \ddots \end{bmatrix}}_{\boldsymbol{A}} \cdot \underbrace{\begin{bmatrix} I_{\text{S1}}^{\text{post}} \\ I_{\text{S2}}^{\text{post}} \\ \vdots \\ I_{\text{L1}}^{\text{post}} \\ I_{\text{L2}}^{\text{post}} \\ \vdots \end{bmatrix}}_{\boldsymbol{x}} = \underbrace{\begin{bmatrix} I_{\text{S1}}^{\text{pre}}(L_{\text{S1}} \parallel \cdots \parallel L_{\text{Sm}}) + I_{\text{S2}}^{\text{pre}}(\dots) + \cdots \\ 0 \\ I_{\text{S1}}^{\text{pre}} L_{\text{S1}} - I_{\text{S2}}^{\text{pre}} L_{\text{S2}} \\ I_{\text{S2}}^{\text{pre}} L_{\text{S2}} - I_{\text{S3}}^{\text{pre}} L_{\text{S3}} \\ \vdots \\ I_{\text{L1}}^{\text{pre}} L_{\text{L1}} - I_{\text{L2}}^{\text{pre}} L_{\text{L2}} \\ \vdots \end{bmatrix}}_{\boldsymbol{b}} \tag{1}$$

$I_{\mathrm{Ln}}^{\mathrm{post}}$ and $v_{\mathrm{load}}(0) = 0$, a supply path inductance of $L = L_{\mathrm{L}} + \max(L_{\mathrm{S1}}, \dots, L_{\mathrm{Sm}})$ and resistance of $R = R_{\mathrm{L}} + \min(R_{\mathrm{S1}}, \dots, R_{\mathrm{Sm}})$, respectively. Solving for the load voltage yields:

$$v_{\mathrm{load}}(t) = \underbrace{\frac{2i(0)LR_{\mathrm{load}}}{\sqrt{\sigma}}}_{A} \cdot \exp\left(-\underbrace{\left(\frac{L + CRR_{\mathrm{load}}}{2CLR_{\mathrm{load}}}\right)}_{B} t\right) \cdot \sin\left(\underbrace{\frac{\sqrt{\sigma}}{2CLR_{\mathrm{load}}}}_{D} \cdot t\right) \tag{7}$$

with

$$\sigma = 2CLRR_{\mathrm{load}} + 4CLRR_{\mathrm{load}}^2 - C^2R^2R_{\mathrm{load}}^2 - L^2. \tag{8}$$

For the resulting rectangular approximation, the first positive and first negative voltage peak of this damped oscillation are considered. The time $t_{\max}$ and $t_{\min}$ of these peaks can be determined by evaluating the derivative:

$$\frac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{load}}(t) = \frac{\mathrm{d}}{\mathrm{d}t} Ae^{-Bt} \sin(Dt) \overset{!}{=} 0 \tag{9}$$

$$\Rightarrow \quad t_{\max} = \frac{\arctan \frac{D}{B}}{D} \quad \wedge \quad t_{\min} = \frac{\pi + \arctan \frac{D}{B}}{D}. \tag{10}$$

Furthermore, the widths of both rectangular pulses are approximated by the time constants of the decaying voltage envelopes τ_{RC} (RC load) and τ_{R} (ohmic load):

$$\tau_{\mathrm{RC}} = \frac{1}{B}, \tag{11}$$

$$\tau_{\mathrm{R}} = \frac{L}{R}. \tag{12}$$

However, the generalized topology described in Fig. 3 cannot be applied directly to every possible supply system topology. In the generalized topology, every load path is connected directly to an individual load without further branching. This might not be the case with tree, ring or otherwise nested structures that can be found in realistic supply systems. Therefore, further worst-case assumptions are necessary to apply the method to more systems. This can be done by discarding all load paths that do not directly connect a load to the investigated node. Thereby, the whole post-switching current flows to the remaining loads, over-estimating the resulting pulses. If this is done for all system nodes separately, a worst-case estimation for all loads can be achieved.

Consequently, with the method proposed in this section, it is possible to approximate the supply voltage pulses of switching events while reducing the computational effort for the solution of a linear equation system and evaluating an analytical expression for each load.

V. Transient Circuit Simulation

The scenarios that have been identified to be potentially critical in the first preselection stage, i.e., scenarios resulting in temporary under- or over-voltages at safety-relevant loads that exceed the respective criteria, are now further analyzed. All scenarios for which the rectangular approximation results in uncritical voltages or where a permanent disconnection from the power supply is identified (total failure; defined as permanent static supply voltage < 100 mV), do not need to be investigated further. For a more accurate analysis, the second stage of the preselection process performs a transient circuit simulation of the specific fault cases. Like the DC circuit simulations, the transient simulation utilizes the MNA based on the supply system's netlist. Again, switching events are assumed to be ideal. Nonetheless, the results of the transient simulation are more accurate than in the previous stage as less simplifications are required. While calculation of a transient simulation with many individual time steps may take longer than the few necessary calculations described in the previous section, it is still faster than an accurate Simscape simulation with more complex nonlinear switching modeling and unavoidable compiling.

To illustrate both preselection stages, an exemplary scenario with two individual supply paths and one load is considered. In accordance with Fig. 3, the parameters of this example are $V_1 = V_2 = 14$ V, $L_{\mathrm{S1}} = 3$ µH, $L_{\mathrm{S2}} = 2$ µH, $L_{\mathrm{L1}} = 1$ µH, $R_{\mathrm{S1}} = 9$ mΩ, $R_{\mathrm{S2}} = 20$ mΩ, $R_{\mathrm{L1}} = 10$ mΩ, $R_{\mathrm{load,1}} = 1$ Ω and $C_{\mathrm{load,1}} = 400$ µF. The switched off (short circuit) current is $I_{\mathrm{sw}} = 657$ A. Fig. 5 shows the resulting approximated worst-case rectangular function and the transient circuit simulation of this scenario.

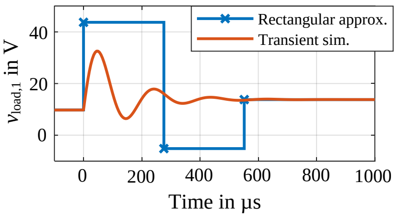

Fig. 5: Exemplary comparison of switching pulse approximation vs. transient simulation

VI. Demonstration

The evaluation method described in this paper has been implemented in MATLAB and is in this section applied to an exemplary power supply system. First, the investigated topology is introduced and the results of the preselection stages are shown. The results are validated based on accurate Simscape simulations. Finally, the performance of the proposed method is discussed.

A. Investigated Supply System

The power supply system that is investigated in this section is depicted in Fig. 6. It consists of four power distribution units (PDUs), two batteries and 32 loads. Inside the PDUs, each connected wire is protected by an individual fuse. The tripping times are set independent of the overcurrent to 6 ms (wires 1 and 5), 4 ms (wires 2-4) and 2 ms (load wires). The fusing currents are set according to the wire's cross sections. The batteries' internal resistances are specified to 10 mΩ and their open circuit voltages are 13.5 V. TABLE 1 shows the parameterization of the loads and their wires. Furthermore, loads 9 and 25 are assumed to be safety-relevant components. In this example, evaluation criteria derived from the VW 80000 [9] standard are used; a supply voltage exceeding 27 V, the maximum test voltage specified in VW 80000, is considered as critical. A critical undervoltage is considered if the voltage drops below 6 V for more than 100 µs.

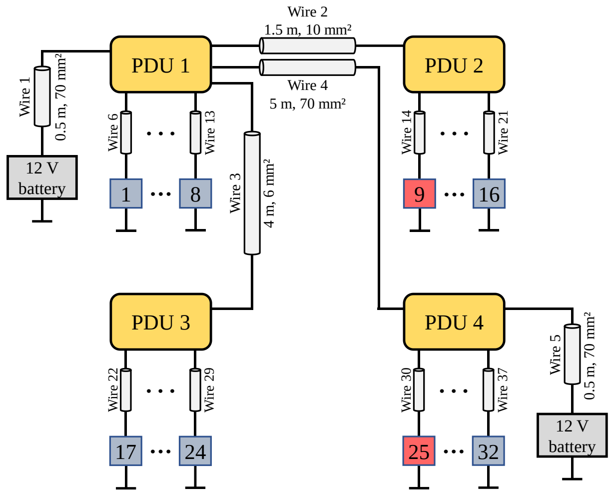

Fig. 6: Investigated power supply system for demonstration of the proposed method

TABLE 1: LOAD PARAMETERIZATION OF INVESTIGATED POWER SUPPLY SYSTEM

PDU	Load	Impedance	Wire (cross section, length)
1	1	0.15 Ω	25 mm², 1 m
	2	100 Ω || 220 µF	0.35 mm², 2 m
	3-8	20 Ω || 47 µF	0.35 mm², 2 m
2	9	1 Ω || 440 µF	1.5 mm², 2 m
	10	0.5 Ω	4 mm², 2 m
	11-16	20 Ω || 47 µF	0.35 mm², 2 m
3	17	0.75 Ω || 440 µF	2.5 mm², 1.5 m
	18	1 Ω || 440 µF	1.5 mm², 2 m
	19-24	1 kΩ (STANDBY)	0.75 mm², 1.5 m
4	25	0.5 Ω || 440 µF	4 mm², 2 m
	26	10 Ω || 220 µF	0.35 mm², 2 m
	27-32	1 kΩ (STANDBY)	0.75 mm², 1.5 m

B. Results of Preselection

The transient voltage stability of the introduced topology is investigated using the proposed method. Therefore, an open circuit fault of each wire, as well as a short circuit at each system node, are analyzed regarding their effect on the supply voltage of the safety-relevant loads. In the investigated system, this results in 83 individual fault scenarios that are analyzed within the first stage of preselection. The approximated worst-case rectangular load voltages for both loads 9 and 25 are depicted in Fig. 7 for all fault cases. A total of 21 scenarios can be excluded from further analysis, as they are either uncritical or lead to permanent disconnection from the supply. The remaining 24 open circuit and 38 short circuit scenarios are investigated in stage 2, as they temporarily violate the defined criteria and may be potentially critical. The resulting voltages of the transient circuit simulations at loads 9 and 25 are presented in Fig. 8. Finally, five scenarios still temporarily violate the evaluation criteria at the safety-critical loads and must be analyzed in an accurate Simscape simulation. The specific fault locations are a short circuit at load 1, load 10, connection of wire 3 and PDU 1, and both ends of wire 4.

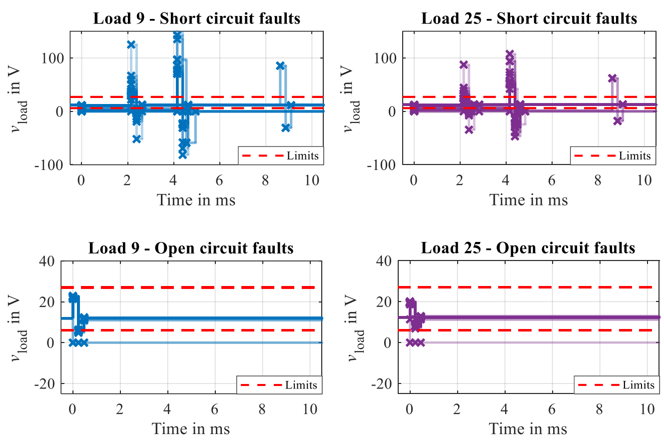

Fig. 7: Preselection stage 1: Approximated voltages of safety-relevant loads for all short and open circuit faults

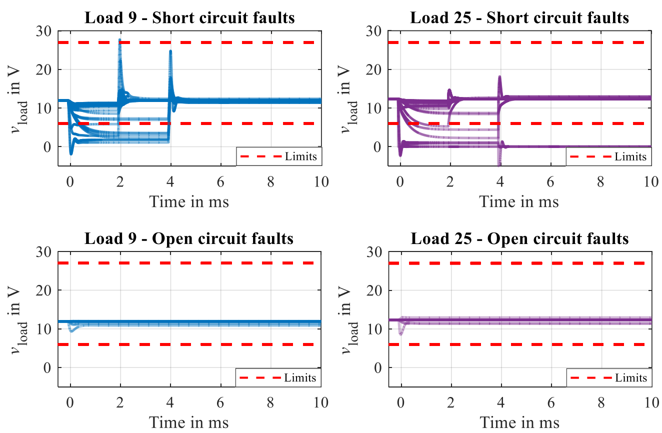

Fig. 8: Preselection stage 2: Transient circuit simulations. Voltages of safety-relevant loads for preselected short and open circuit faults

C. Validation

According to the preselection, only the remaining five fault scenarios need to be investigated in a final Simscape simulation. However, to validate the proposed method and show that no critical scenarios have been missed, all 83 fault cases are also simulated in Simscape.
In Fig. 9, all simulated load voltages of loads 9 and 25 are depicted for both fault types.

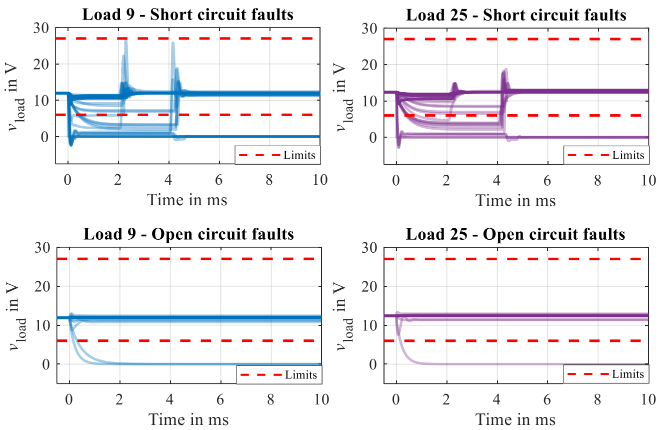

Fig. 9: Accurate Simscape simulations of safety-relevant load voltages for all short and open circuit faults

The analysis of these Simscape results yields the same critical fault cases as the proposed preselection process. In total, 14 of the 83 fault scenarios lead to a total failure at either or both of the safety-relevant loads (11 short circuits, 3 open circuits). Additionally, five short circuit scenarios temporarily violate the voltage-time criteria. Therefore, the five remaining potentially critical cases of the preselection process proved to be actually critical. Most importantly, no critical scenarios have been missed by the proposed method.

D. Performance

As the objective of the proposed evaluation method is to accelerate the analysis of transient voltage stability, the performance gain for the investigated system is analyzed. All calculations are executed on an Intel i7-9700 processor with 16 GB RAM. TABLE 2 shows the total runtimes for both preselection stages. As one fault simulation of the investigated system on average takes about 62 s in Simscape using the models presented in [6], the complete workflow proposed in this paper (Fig. 3) takes about $t_{\text{total}} = 9.8\text{ s} + 17.3\text{ s} + 5 \cdot 62\text{ s} \approx 337\text{ s}$. In contrast, simulating every scenario using Simscape took $t_{\text{total,Simscape}} = 5112\text{ s}$ (see Fig. 10). This results in 93 % reduction in computation time.

For larger and more optimized practical supply systems this number may be much larger because of the increased number of possible fault locations.

TABLE 2: PERFORMANCE OF INVESTIGATED EXAMPLE

	Analyzed scenarios	Remaining scenarios	Elapsed time
Preselection stage 1 (rectangular approximation)	83	62	9.8 s
Preselection stage 2 (transient circuit simulation)	62	5	17.3 s

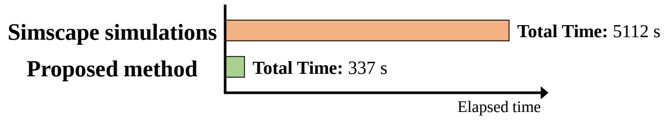

Fig. 10: Total elapsed time comparison of proposed method versus complete Simscape simulations

VII. CONCLUSION

In this paper, a fast method for evaluating the transient voltage stability of automotive power supply systems in case of wiring faults has been presented. Instead of accurately simulating every possible fault scenario in a circuit simulation tool with numerical integration, an efficient preselection process of relevant fault scenarios is proposed. Based on analytical calculations and worst-case assumptions, the system's fault behavior is first approximated by rectangular functions. Potentially critical scenarios are further analyzed using transient circuit simulations, while still maintaining the worst-case assumption of ideal switching behavior. Finally, only the scenarios remaining after this preselection process need to be simulated in an accurate but time-consuming simulation. The method has been demonstrated based on an exemplary power supply system. The computational time for transient voltage stability analysis could be reduced by 93 %. Furthermore, a Simscape simulation of every considered scenario showed that all critical fault cases were discovered by the proposed method.

Future works may focus on further optimization of the developed method. Besides improving the approximation methods, implementation in C++ or another compiled language may result in significant acceleration. Finally, this method can be integrated into a superordinate workflow that selects and optimizes highly reliable power supply systems for future vehicles.

ACKNOWLEDGMENT

The work presented in this paper was partially funded by the AK 30 working group within the Research Association of Automotive Technology (FAT) of the German Association of the Automotive Industry (VDA). The responsibility for this publication is held by the authors only.

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