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A New Test System for the Simulation-Based Emulation of Highly Dynamic Power Supply Faults

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***Abstract*— Many future vehicles will be characterized by automated driving features which demand an outstanding reliability of safety critical components. To ensure the needed safety in operation of the systems, the power supply system must support a fail-operational function. Typical component tests regarding the supply system are simplified and cannot consider the propagation of voltage pulses or drops along the power supply system and faulty system interactions. This paper proposes a new testing approach. The propagation of power supply system faults in a supply network is simulated first, and the time dependent voltage profiles are calculated for each attached component individually. In a second step the voltage profiles gained from simulations are fed by a highly dynamic voltage source to the components and possible interactions are analyzed in this special setup. The new test method is presented and analyzed. In an exemplary automotive system two redundant electronic components are interacting via a CAN interface. It is shown how highly dynamic power supply system faults can lead to unexpected system interactions. The need for better testing methods is confirmed.**

Keywords*—hardware-in-the-loop; HIL; automotive component test; advanced safety requirements; dynamic fault emulation; on-board power supply system.

I. INTRODUCTION

Highly reliable automotive power supply systems are required for future automated vehicles. As the driver will no longer be available as a fallback solution, the system itself must be able to guarantee functionality in all situations, even in the event of power supply faults (fail-operational) [1]. The electronic components realizing the automated driving features, the power supply system and the communication networks must be designed accordingly. Sophisticated system testing becomes mandatory to guarantee the required safety.

The influence of power supply disturbances on components are often tested according to ISO 16750 [2] or ISO 7637 [3], where typical voltage profiles over time are emulated and the behavior of a **D**evice **u**nder **T**est (DUT) during the fault exposure is analyzed. Testing against such voltage profiles is important, but reality can be more complex. **H**ardware-**i**n-the-**L**oop (HIL) is another common approach for functional testing of electronic components and systems. Electronic components are operated in an emulated environment controlled by simulation models and the behavior of hardware and software is analyzed under different operating conditions. For example, the recently published UN regulation No. 157 for automated lane keeping systems [4] suggests the use of HIL approaches for validation of safety requirements. In terms of advanced safety requirements, backup or redundancy concepts are also introduced to increase the safety of the overall system. This leads to more complex component testing because of interaction between components and cannot be addressed by simple tests. Therefore, there is a need for parallel testing of safety-relevant features in the system’s context.

In this work, an open-loop supply system testing approach is applied to exemplary redundantly designed DUTs which communicate via a CAN-bus. The influence of highly dynamic power supply system faults events on a communication channel is investigated. An exemplary power supply system topology is presented, and failures are simulated. Simulations provide the test voltage signals for both components during complex failure events. The voltage signals are replayed by arbitrary function generators, amplified by special voltage amplifiers which are connected to DUTs. The test methodology, the setup and the application are discussed in this paper.

II. POWER SUPPLY COMPONENT TEST METHODS

To evaluate the behavior of a component during a power supply fault, different approaches can be used. Standardized tests emulate power supply faults by providing typical voltage signals to a single component. HIL approaches can be more complex and can handle system interactions. One or more components are operated in an emulated environment that might consider specific details of the system. In this section, both methods are discussed and a HIL-method for the test of power supply failures in a system's context is proposed.

A. Standardized Tests

Standardized tests are used for evaluating the behavior of a DUT during power supply faults in the development process of automotive components. Different test scenarios are described in standards such as ISO 16750 [2], ISO 7637 [3] or OEM specifications. These tests are based on different fault scenarios, which have been observed in the past and for which voltage profiles have been standardized. Components are tested against these disturbances.

Figure 1 shows a possible, flexible realization of such tests. The DUT is supplied by a power amplifier, which is controlled by test signals representing the voltage profiles defined in the standard (in reality, test pulses are generated mainly by switched RC or RLC circuits). A residual bus emulation is used to emulate the desired operating state of the DUT. The bus system emulator is normally supplied by its own source and therefore not exposed during the test of the DUT.

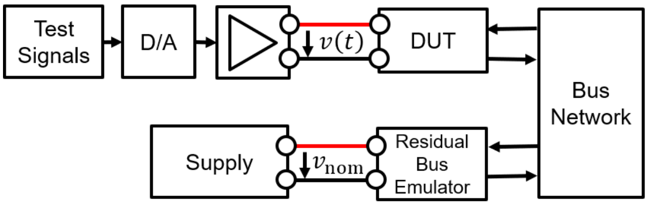

Fig. 1: Simplified test method defined in standards

While testing against fixed voltage profiles is important, reality can be more complex. The voltage profiles are often simplified and there were examples in the past where actual voltage transients have caused DUT malfunctions, which could not be reproduced with the standardized test pulses [5]. Also, these tests are designed to test a single component during fault exposure. Rather than possible interactions between components, only interactions with a residual bus emulation are considered. Furthermore, the components that are directly communicating with the DUT are not exposed to the faults at the same time in the overall systems context. Parallel testing of safety-relevant components this way would not consider disturbance propagation along the power supply system. Therefore, this method is not sufficient when advanced safety requirements are specified.

B. Hardware-in-the-Loop

A general distinction between **C**ontroller **H**ardware-**i**n-the-**L**oop (CHIL) and **P**ower **H**ardware-**i**n-the-**L**oop (PHIL) can be made [6]. Typically, in CHIL applications the DUT is a controller and the power elements are modelled within a simulation environment whereas in PHIL applications an emulation of the power flow between the device and the simulated system is realized. To emulate the power flow, power amplifiers are needed. A comparison between switched and linear power amplifiers for PHIL applications is given in [7]. A possible PHIL setup for the test of a single automotive component based on the previously discussed setup in Figure 1 is depicted in Figure 2. The system is expanded by a simulation environment and a sensor measuring the DUT feedback by voltage or current measurements.

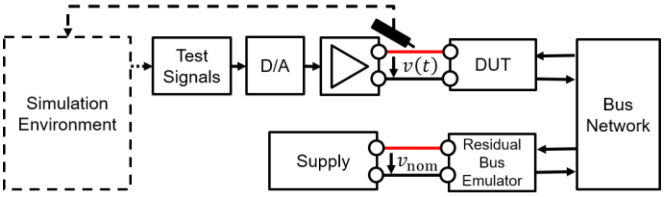

Fig. 2: Power Hardware in the Loop Emulation concept for a single component test

In the automotive sector, CHIL tests are generally used to test control algorithms and HW/SW interactions [8,9] during development. PHIL tests have been used for battery emulation [10] or to test charging systems [11]. Another PHIL application is the emulation of loads [12]. Today, PHIL component tests are not widely applied. The general concept of PHIL is promising in generating realistic power supply test cases for single components and could also be expanded to multiple components. However, closed-loop stability of the overall system is often a challenge for operating PHIL test systems [7].

C. Proposed Concept of PHIL Testing of Automotive Components

In this work, an open-loop approach for the test of components in parallel is proposed. Figure 3 shows the proposed concept.

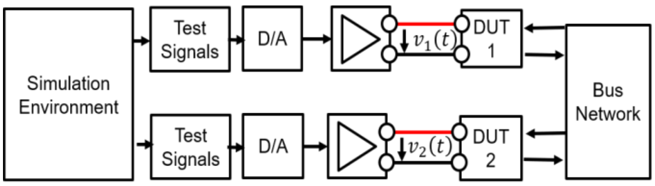

Fig. 3: Proposed test method to evaluate safety requirements of redundantly designed components

The test system uses time dependent voltage profiles gained in detailed power supply system simulations. The node voltages in the simulation are used to emulate the voltages at two DUTs simultaneously. By using an open-loop approach, taking care of the closed-loop stability is not needed. The pulse propagation and the difference in the fault amplitudes at both DUTs are considered by a power supply simulation. No remaining bus emulation is considered, since it is assumed that the components communicate directly with each other.

III. POWER SUPPLY SYSTEM

For the energy supply network many topologies are available. As shown in [13], combinations of different voltage levels, converter concepts and energy sources may be considered. Also, the diagnosis and protection concept influence the robustness of the overall system. Therefore, the design of a highly reliable power supply system is a complex task. In this contribution, an exemplary power supply topology is investigated to demonstrate the proposed testing concept. The chosen topology is described and the fault scenario and simulation results are discussed.

A. *Power Supply Topology for Demonstration*

Figure 4 shows the selected power supply topology for demonstration purposes. The redundantly designed loads are named as DUT 1 and DUT 2 (Backup) and consist of a control and a power stage. The control stage consists of a microcontroller (µC), which generates the control signals for the power stage and realizes the communication over the CAN bus. On the left side, a DC/DC converter is used to supply the system and converts a high voltage (e.g., 48 V or HV) to the on-board system voltage of 12 V. On the right side, a 12 V battery is used for redundant supply. Two **P**ower **D**istribution **U**nits (PDU) with electronic fuses are used for wire protection. These electronic fuses feature a self-protection, which shuts down the load when the current exceeds five times the nominal load current for more than 16 µs. In total, there are three loads connected to the power supply system. Furthermore, a simple high current consumer is assumed with a current consumption of 50 A. The simulation models are described in [14]. Validation of the models for dynamic switching events and fault simulations are described in [15].

B. *Fault Scenario and Simulation Results*

The total load of the microcontroller in the control stage is represented by a resistor and an input protection circuit. The microcontroller supply is protected by a circuit consisting of a reverse polarity protection diode and a stabilizing capacitor of 70 µF. The total current consumption of the control stage is 2.5 A. The microcontroller controls a power stage, which is modelled by a resistive load parallel to a stabilizing capacitor (see Figure 4). In total, the current consumption of each DUT is approximately 8.5 A and assumed to be static during the short circuit. The high current consumer is modeled as a 0.25 Ω resistor. The parametrization of the electronic fuses is given in Table 1.

TABLE 1: FUSE TRIGGER CURRENTS

Load	Fuse Trigger Currents	
	Nominal load current (> 500µs)	*Self-protection shut-down current **(> 16 µs)***
DUT 1	9 A	45 A
DUT 2	9 A	45 A
High Current Consumer	80 A	400 A

In this setup, several possible faults in the on-board power supply system can be emulated. For demonstration purposes of the general test concept, a short circuit at the high current consumer is simulated, which has been examined as a critical scenario in this configuration. The examination of further scenarios and ideal test coverage is not within the scope of this paper. The simulation results (node voltages $v_{\mathrm{DUT},1}(t)$ and $v_{\mathrm{DUT},2}(t)$) can be seen in Figure 5.

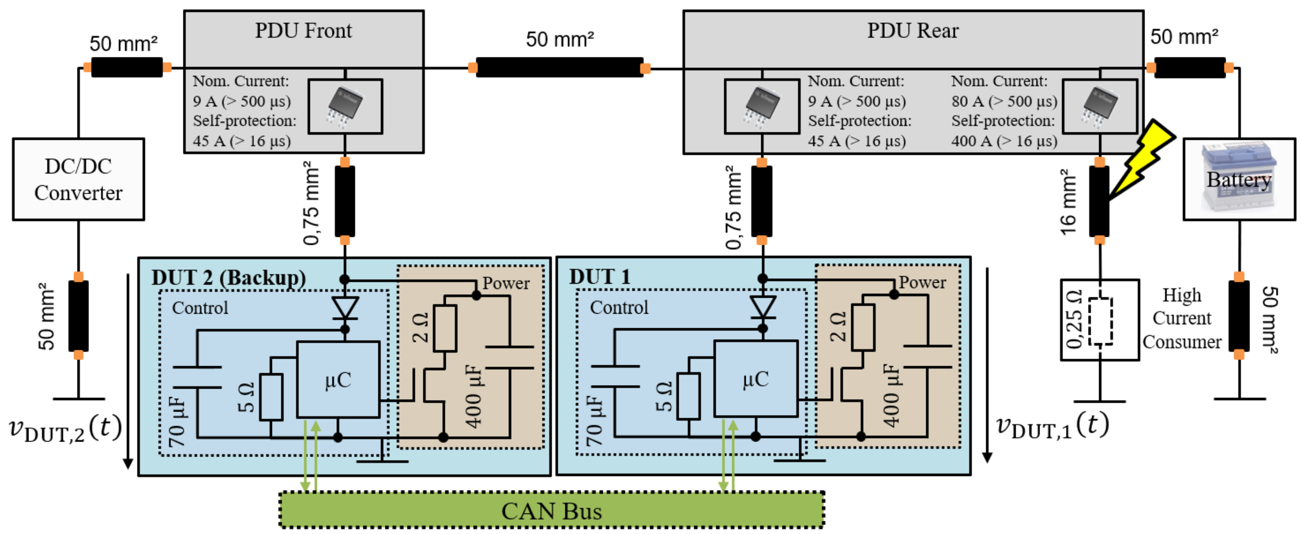

Fig. 4: Exemplary Power Supply Topology

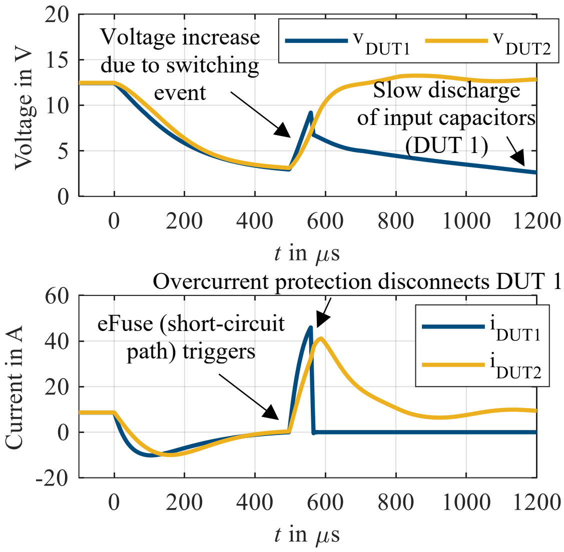

Fig. 5: Simulation results of the investigated fault scenario

The short circuit fault happens at 0 s. The short circuit current on the path of the high current consumer rises until it reaches 400 A, which triggers the self-protection mechanism of the electronic fuse at approximately 490 µs. This switching process leads to a rapid increase in voltage, which results in a high rise in current to charge the input capacitors of both DUTs. The resulting current on DUT 1 is high enough to trigger the self-protection shutdown mechanism of the electronic fuse. Whether DUT 2 can maintain its function during the fault exposure should be analyzed.

IV. PHIL Test Setup

The setup shown in Figure 3 for testing power supply system fault scenarios has been implemented. It is applied to the power supply setup from Figure 4 and the fault scenario discussed in the previous section is emulated. The hardware setup is described and a characterization of the used amplifiers in the frequency domain is given. Two Atmel Microcontroller development boards are used for the control stage of the DUTs. The DUTs are exchanging information over a CAN bus. The influence of the power supply fault on the communication lines are investigated.

A. Voltage Emulation

Figure 6 shows a photo of the total test setup according to the schematic in Figure 3. The system's behavior is computed in Simulink/Simscape, which functions as the simulation environment. The resulting node voltages at the DUTs are the test signals. The power stage of the DUTs is represented by resistors and capacitors.

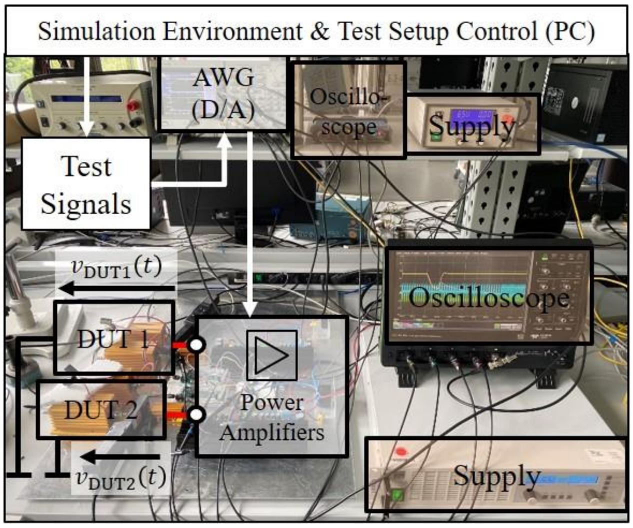

Fig. 6: Test setup

A two channel Arbitrary Waveform Generator, AWG (Tektronix AFG 3152C), is controlled by a PC with Matlab. The AWG provides the control signals for the power amplifiers. The amplifiers are modified Class-AB audio amplifiers (based on TDA7293 ICs), which are capable of amplifying DC signals. Linear amplifiers are chosen because of their high dynamic properties [7]. Voltages in the range from 50 V to -50 V and currents up to 50 A can be supplied to a DUT by each amplifier. The transfer functions are shown in Figure 7.

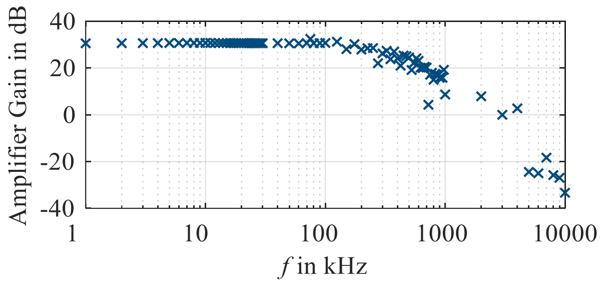

Fig. 7: Frequency domain characterization of the TDA7293 amplifier boards

For frequencies below 200 kHz, the amplifier gain of approximately 30.4 dB can be considered constant. The cutoff frequency is 230 kHz. Since the voltage profile time constants to be emulated are in the time range of several tenths of a microsecond, the chosen amplifiers are suited to emulate the power supply fault.

B. Emulation Results

Figure 8 shows a comparison between the emulated and the simulated DUT voltages and the CAN bus voltages. The emulated waveforms are very similar to the simulated waveforms. The emulated voltage of DUT 1 shows a deviation when the over-current protection of the electronic fuse is triggered. The voltage at the output of the amplifier is briefly lower than the previously determined simulation voltage. This effect is caused by the amplifier output behavior when driving capacitive loads. To compensate the amplifier behavior for the fast-switching event in combination with a capacitive load, the control signal needs to be adjusted. This could be improved by measuring the output voltage of the amplifier and regulating the control signal to adjust it accordingly instead of using fixed control signals with an AWG, but it can be seen that the communication already fails before this effect happens. During the test, the supply voltage drops below 5 V, which first leads to a decrease of the differential CAN signal. Moreover, the communication fails since the supply voltage drops even further until the minimum of 3.2 V is reached. Afterwards, both DUTs are trying to restart. Since the voltage on DUT 1 cannot be stabilized only DUT 2 restarts after approximately 10 ms. DUT 1 fails to restart and the communication is interrupted.

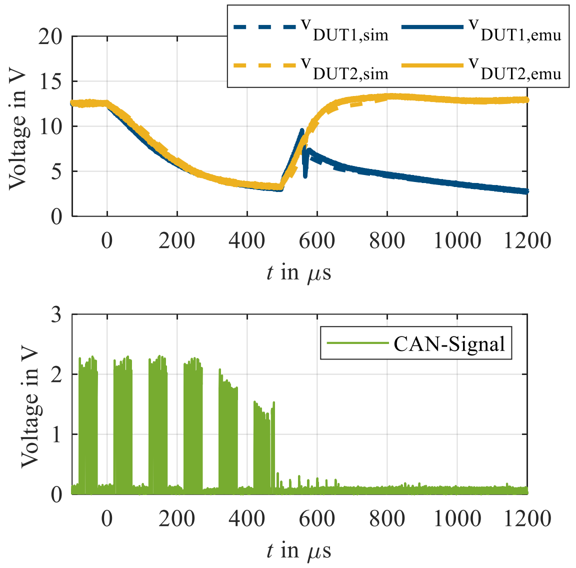

Fig. 8: Emulation of the power supply fault scenario and assessment of the communication between two redundantly designed components

V. Conclusion

In this contribution, an HIL method to test networked safety-critical components during power system failures has been proposed. The power supply voltages during a fault event are calculated by a network simulation. The method has been applied to an exemplary power supply system topology. The influence of a power supply fault on the communication ability of two DUTs has been investigated. It has been shown that the general concept of the method is useful and problems can be found that cannot be found with conventional testing. The model-based fault analysis offers more test cases than standard tests can provide.

Further work may improve the test method by implementing a closed-loop testing approach in a real-time environment, or may focus on the automatic identification of critical faults, which could improve test coverage.

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References

[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*, Rome, Italy, 2019.

[2] ISO, “ISO 16750-2 Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 2: Electrical loads”, 2012.

[3] ISO, “ISO 7637-2 Road vehicles – Electrical distrubances from conduction along supply lines only”, 2011.

[4] UN Regulation, “UN Regulation No. 157 – Automated Lane Keeping Systems (ALKS)”, 2021.

[5] R. K. Frazier and S. Alles, "Comparison of ISO 7637 transient waveforms to real world automotive transient phenomena," *2005 International Symposium on Electromagnetic Compatibility, 2005.*

[6] A. Spina, „Advanced laboratory testing of smart grid applications with power hardware-in-the-loop approach”, Dortmund: Technische Universität Dortmund, 2021.

[7] F. Lehfuss, G. Lauss, P. Kotsampopoulos, N. Hatziargyriou, P. Crolla and A. Roscoe, "Comparison of multiple power amplification types for power Hardware-in-the-Loop applications," *2012 Complexity in Engineering (COMPENG). Proceedings*, 2012, pp. 1-6.

[8] R. Rodrigues da Silva, E. L. Silva Teixeira, A. Murilo and M. M. Dias Santos, "A hardware-in-the loop platform for designing and testing of electric power assisted steering," *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 5113-5118.

[9] K. Enisz, D. Fodor, I. Szalay and L. Kovacs, "Reconfigurable real-time hardware-in-the-loop environment for automotive electronic control unit testing and verification," in *IEEE Instrumentation & Measurement Magazine*, vol. 17, no. 4, pp. 31-36, Aug. 2014

[10] O. König, C. Hametner, G. Prochart and S. Jakubek, "Battery Emulation for Power-HIL Using Local Model Networks and Robust Impedance Control," in *IEEE Transactions on Industrial Electronics*, vol. 61, no. 2, pp. 943-955, Feb. 2014.

[11] A. Popov, M. Tybel and M. Schugt, "Power hardware-in-the-loop test bench for tests and verification of EV and EVSE charging systems," *2014 IEEE International Electric Vehicle Conference (IEVC)*, 2014, pp. 1-8.

[12] L. T. Peters, C. Weissinger, M. Baumann, J. Taube and H. -G. Herzog, "Emulation of High-Dynamic Automotive Loads using parallel MOSFETs in Linear Mode Operation," *2021 IEEE Transportation Electrification Conference & Expo (ITEC)*, 2021, pp. 513-518.

[13] S. Schumi, “Energy and Supply Concepts for Automated Driving,” in 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), Nottingham, 2018.

[14] M. Rübartsch, M. Gerten and S. Frei, "A Model based Test Environment for the Analysis of the System’s Behaviour during Power Supply Faults," *AmE 2021 - Automotive meets Electronics; 12th GMM-Symposium*, 2021.

[15] M. Gerten, M. Rübartsch, S. Frei, “Models of Automotive Power Supply Components for the Transient Analysis of Switching Events and Faults”, in *AmE 2022 - Automotive meets Electronics; 13th GMM-Symposium*, 2022.