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Evaluating 48 V and new architectures for the low voltage power supply

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ABSTRACT: The paper addresses the recently renewed discussion about the introduction of 48 V as the main voltage level for power distribution in the automotive low voltage (LV) network beyond mild hybrid functionality. Tesla introduced 48 V power distribution in the Cybertruck in 2023, so far being the only OEM (Original Equipment Manufacturer) taking this step and advocates a 48 V standardization. Most OEMs have however, not changed yet to a 48 V power supply, despite the obvious advantages in power capability, and the predicted weight and cost savings. Among other factors, the large legacy effect of the long established 12 V applications as well as high initial investments for a redevelopment of commodity components have kept OEMs from increasing the main LV level to 48 V. But as new technologies and functions are introduced into modern vehicles, the limitations of a 12 V based power supply is becoming an obstacle that is hard to overcome without supersizing the existing power supply and its underlying architecture beyond a reasonable degree. A new potential trigger point is the adoption of 48 V in conjunction with an introduction of zonal architectures. The goal is a simplification of the complex wiring harness and enabling the supply network to power new vehicle features which demand a high-power capability on LV level and often have increased requirements in terms of availability and robustness of the supply. Currently, a lot of uncertainty remains about the if, when, and for which vehicle segments, equipment and markets, such a major step is technically as well as financially feasible. The final conference contribution will cover several aspects of this many-faceted discussion, give some background information on the ongoing efforts in adjusting the regulatory framework, and shed some light on enablers as well as potential pitfalls for the transition to a 48 V power supply. System simulation will be presented as the tool of choice to evaluate technical aspects and to prove the validity of new supply concepts in an early stage.

KEY WORDS: 12 V, 48 V, low voltage, power supply network, system simulation, E/E architecture, standardization

1. INTRODUCTION

While the idea of an increased voltage level in the automotive low voltage power supply network was discussed many times over the last decades [1,2], until today, this adaptation has not seen a mass market introduction despite its clear advantages. The greatly increased power capability, as well as weight and cost saving potential especially for the vehicles wiring harness, are often stated benefits of an upwards shift to 48 V. Some exceptions where 48 V was used nonetheless are mild hybrid applications, for example when the higher voltage level was required to reach the necessary power capability to support drivetrain functions, or the local supply of high-powered active chassis components used by some premium OEMs.

There is a multitude of arguments that prevented the successful introduction of 48 V for LV power distribution. Many of these issues revolve around the anticipated high costs, be it for the new development of already existing components on 12 V, the effect of initially low sales volumes of 48 V devices, higher prices for semi-conductors with the necessary increased voltage tolerance, or the rising costs expected for a complete overhaul of an established supply basis, to name but a few. Apart from these financial issues, there are also technical concerns that need to be addressed. These include an increased risk of light arc occurrences, the danger in case of a short circuit from 48 V to potentially remaining 12 V branches and the resulting malfunction and destruction of the affected devices, or the loss of ground at components which are connected to both voltage levels with a similarly dramatic outcome. Despite these reservations, new vehicle functions and their increased power requirements are calling for a major improvement of the low voltage supply system in tomorrow's vehicles, and an adoption of 48 V is gaining more and more attention as a possible solution.[3–5]

2. Current discussion

2.1. Potential enablers for an introduction of 48 V

While the steady increase of the overall power demand within the automotive low voltage network has not yet prompted the

OEMs to change their conventional 12 V based power generation and distribution, the power and availability requirements of some upcoming vehicle functions might force them to reconsider.

Autonomous driving (AD) is largely seen as one of the key features of tomorrow's vehicles, but it comes with high requirements on the power supply system. Estimations for the power consumption of the necessary high-performance computers needed for high level AD vary strongly, but typical indications point towards a level of 500 W to 1000 W of continuous power demand, effectively tripling the average typical LV power demand in today's passenger cars [6]. Additionally, all components related to AD must be considered highly safety critical, often bringing the need for redundancies of hardware and supply.

Other examples are active chassis, brake- and steer-by-wire systems, all of which have high power and availability requirements. This brings the need for a high-power LV supply and new architectures to ensure independence of redundant systems in case of errors like short circuits in the network. The occurrence of high reverse currents coming from steer-by-wire or active chassis systems brings the additional risk of over-voltages, should the supply system not be powerful and dynamic enough to deal with such events.

New and demanding requirements also occur due to changes of the regulatory framework, e.g. stricter CO_2 or pollutant limits for vehicles using an internal combustion engine (ICE). For this example, high-powered electrically heated catalysts for improved exhaust pipe treatment could be a feasible solution.

Each of the beforementioned functions is likely difficult to realize using a 12 V based LV power supply and could hence act as an enabler for the introduction of 48 V into the mass market. And while a minimal setup in form of a local subnet, frequently referred to as an "isle network", where only one single high-powered device is supplied with 48 V, is still a viable solution, the availability of the new voltage level in the vehicle could spark the shift of a number of other components as well.

2.2. Potential candidates for a shift to 48 V

Apart from these 'enabler loads', also other application with high power demand and a high activation time during operation (see Fig. 1) can be considered suitable candidates for a shift to 48 V due to the resulting overall current reduction. A complete shift of all 12 V components to 48 V, especially for loads with a very low power consumption seems unnecessary from component perspective. However, it remains an option when considering safety concerns that accompany mixed voltage level networks, like higher to lower voltage level short circuits with common ground or critical loss of ground scenarios. [7]

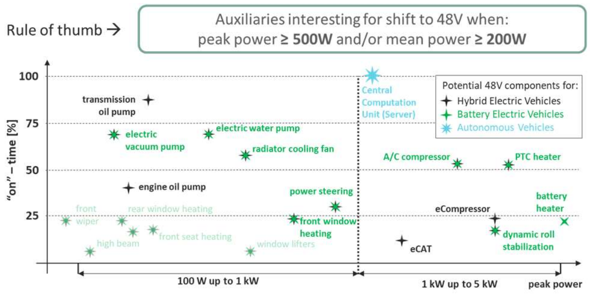

Figure 1: Typical load transfer map for HEV and BEV; bold plot indicates suitability for 48 V according to the applied rule.

2.3. Step-by-step transition and potential pitfalls

The redevelopment and qualification of applications for 48 V will take time and not all potentially interesting loads can be shifted within one vehicle development cycle. This results in the need for transitional architecture solutions due to legacy. But there are a number of pitfalls in terms of safety concerning the afore-mentioned mixed voltage level systems as well as on an architectural level. Employing two LV battery systems within the co-existing voltage levels will be very costly, with especially the 48 V lithium-ion battery driving costs due to the battery management system (BMS) it requires.

A potential complication could be the supply of key-off loads, which are loads that must be supplied while the vehicle is parked. Typical examples are the vehicle alarm or the key-less access systems. Overall, these loads sum up to a key-off current consumption of typically between 20 to 100 mA. These loads are usually supplied by the 12 V lead-acid battery. In a scenario where some of the loads that need to be supplied while parking are shifted to 48V while others are not, both voltage levels would have to be supplied, creating the need for two batteries or other solutions involving power conversion like low powered DC/DC converters.

Another issue could be the increasing demand for supply redundancy for safety critical loads. As a standalone configuration the standard 12 V network already contains a basic level of redundancy by employing a main power source as well as a buffer battery. When moving parts of the safety critical loads to a different network, the safe supply of the loads must still be guaranteed, even if one of the power sources should fail. A distribution of such loads to both voltage levels would thus require additional power sources.

Lastly, when considering the power supply net in combustion or mild hybrid vehicles, where no large energy storage like the HV battery is available, the generator as main power source is not or only to some extend available during stand-still. Despite this, all relevant systems on two voltage levels must be supplied sufficiently in these vehicles as well, which might once again bring the need for additional power sources.

2.4. New zonal architectures

Beyond the 48 V discussion, there is a trend to simplify the complex controller network by reducing the large number of separated electronic control units (ECUs). The idea is to integrate all ECUs belonging to one major control domain (e.g. vehicle body, chassis or powertrain domain) into fewer, more powerful ECUs. In a next step, many OEMs want to introduce a zonal architecture, where ECUs are clustered not according to their domain affiliation, but to their location in the vehicle. This change is of special interest for the power supply network, since the zone controllers (ZC) serving as local command centers within the zones can ideally also be used as sub-distribution centers for the power supply (see Fig. 2).

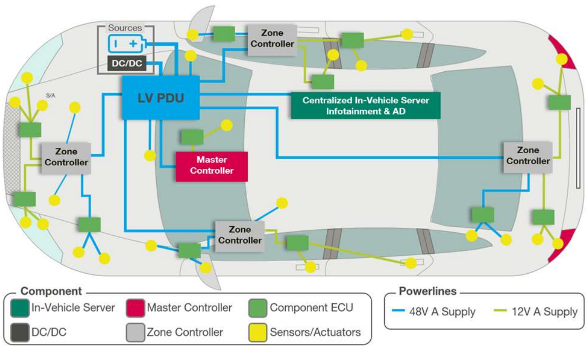

Figure 2: Zonal supply architecture including a 48 V main power distribution network and a local 12 V conversion.
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Target of the sub-distribution within a zonal architecture is to optimize the wiring harness also for power supply. This strongly reduces the overall cable length in the vehicle and additionally allows for an easier integration of the now smaller sub-part of the harness into the vehicle during assembly.[8]

By combining such a zonal architecture with the introduction of a 48 V based main power distribution network, the overall system efficiency can be increased and the wiring harness reduced even further. Fig. 2 shows an example for an architecture that is based on local ZCs which are connected to a central PDU (Power Distribution Unit). Here, the power is fed into the LV supply network by a HV to 48 V DC/DC converter, distributed to the ZCs via a PDU, and then further sub-distributed to the final loads within the zones. A 48 V battery is used to support in situations with a high-power demand, acts as fallback solution (i.e., redundant power supply) in case of DCDC failure and to supply key-off loads. The ZCs include small 48 V to 12 V DC/DCs which allows for a local supply of loads from both voltage levels for a fully hybrid network. In another configuration the PDU is omitted as a central distribution point and the LV power sources are directly linked to the ZCs which exchange power among each other. The latter, also called a "backbone topology" is depicted in Fig. 3 (right) together with the PDU centric version introduced in Fig. 2.

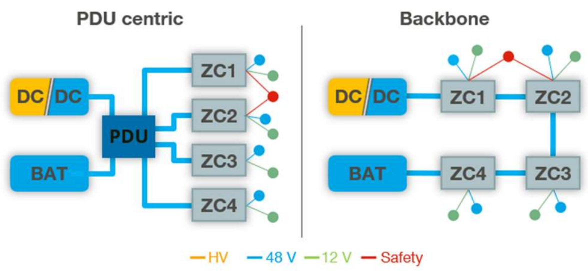

Figure 3: Two topology variants for a 48 V based LV supply net.

The topologies differ in the way the power is routed through the vehicle, namely in a centralized star-shaped pattern or along a linear backbone, both offering individual benefits as well as disadvantages. By installing additional network separation devices, e.g. inside the PDU and ZCs, a redundant supply of safety critical loads can be achieved using a dual supply either from two ZCs, as is indicated in Fig. 3 in red, or directly from the PDU.

Such architectures allow the hybrid use of components for both LV levels and thus support transition scenarios in which OEMs and component suppliers alike gradually move from 12 V to 48 V where beneficial. These are just two possible examples within a large solution space that needs to be explored in order to find an optimal solution. The latter will depend on a long list of individual requirements for each system and the solution might vary strongly between different car brands, vehicle segment and equipment.

While the OEMs will likely strive to keep the number of supply architectures as small as possible, ideally even across their different drivetrain platforms, we can expect a much larger variety of different power supply network configurations in the next vehicle generations, which in terms will lead to a more colorful landscape of needed LV components.

2.5. Architecture impact on component requirements

One of the main hurdles for the introduction of 48 V is the lack of readily available components from the automotive suppliers, who in turn point out a missing demand to justify the development of 48 V auxiliary components to replace existing 12 V applications.

Furthermore, when comparing different solutions in the large space of possible configurations, the additional challenge of a strong dependency of the component requirements on the system they are used in becomes visible. In the past, the requirements for example for a HV to LV DC/DC converter mostly varied within a certain interval of the peak output power and variations of the integration space and the cooling concepts, but now entirely new types and classes of DC/DCs are emerging, dependent on the architecture. Here, the required power ranges from many kilowatts for main DC/DCs down to a few watts for key-off supply with miniature so-called micro-DC/DCs. Highly available DC/DCs might be needed to comply with high ASIL requirements, and embedded 48 V to 12 V DC/DCs in ZCs enable a hybrid load supply. Thus, in order to anticipate the needs and develop the right products and features, it is crucial among the supply chain, to understand and evaluate the impact of architectural decisions. Likewise, the OEMs should involve their supplier base in their definition of new architectures to ensure the timely development of the components required to realize them.

2.6. Changes of the regulatory framework

Within the regulatory committees the industry is working on ways to better facilitate 48 V and to fully utilize its advantages for the LV power supply net. The currently applicable standard, ISO 21780, was introduced targeting 48 V as part of a mild hybridization, allowing for extensive voltage dynamics due to high currents during electric drivetrain boosting and energy recuperation when braking.

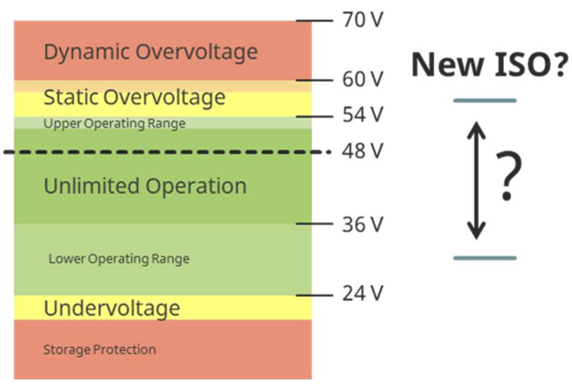

Figure 4: Review of voltage limits according to ISO 21780.

For an application as main LV power distribution in HV vehicles where the LV supply is stabilized by a DC/DC converter, such high voltage dynamics are no longer meaningful and new standardization is ongoing. Trends within this discussion, especially an adjustment of the required voltage limits (see Fig. 4), will be presented in the conference contribution.

3. Physical parameters and system simulation

Due to the growing complexity and the many interdependencies within the LV network, evaluating the impact of technical innovations and alterations is becoming increasingly difficult. Conventional analytical methods quickly reach their limits and even high-level predictions become tricky or even misleading when discussing system dynamics. Direct measurements of physical system behavior on the other hand are often not feasible, because building a suitable prototype network is too costly and time consuming or simply because the needed system components are not available on the market yet. Hence, simulation has become the go to method for impact analysis and early system validation when it comes to power supply net evaluations.

When modelling a large system like the automotive LV power supply network finding the right level of detail is crucial. The necessary as well as feasible depth of modelling depends strongly on the question to be answered with the targeted simulation, the computational limitations as well as the availability of parameterization data. Mixing sub-models of different fidelity levels in one overall system model can lead to low accuracy, numerical simulation issues or even outride false test results. Similarly, simulation time steps must be carefully considered and adjusted to the effects that are to be studied.

When investigating electric system behavior like voltage quality, the occurrence of over- and under-voltages, peak currents and slew rates, the system reaction is typically monitored in a timeframe of milli-seconds and with a resolution in the lower micro-second range. Special dynamical use cases like a hard short circuit event with its occurring large current slew rates up to several dozens of amperes per micro-second even requires resolutions in the lower nano-second range and detailed high-fidelity models for an adequate study. Other automotive-specific use-cases like the redundant supply of safety-critical systems during a so-called minimum risk maneuver (MRM) on the other hand require an observation over several seconds, and corresponding simulations can usually be performed with simplified averaging models and lower resolution.

In the following sections examples are given, where system simulation can help to understand and quantify some of the effects of a transition from a 12 V based LV power supply towards 48 V and to examine the impact of the used supply architecture on the system behavior. The results are punctual investigations in a subjectively chosen setting and are meant to showcase the value of simulation as a method for evaluation rather than claiming to precisely represent the benefits or disadvantages of a changed voltage level or a specific supply topology.

3.1. Wire cross-section reduction

An argument often stated as an important advantage of 48 V is the reduction of wire cross-sections to safe weight and cost of the vehicle wiring harness. The degree of reduction to be assumed when calculating such benefits is a matter of discussion, however. Apart from a limitation in respect to mechanical stability of wires (risk of bending, ripping and vibrating etc.) there are opposing efficiency and voltage stability issues to be taken into account.

Due to lower currents, when employing a higher voltage level and an assumedly constant power demand of a load, the conduction losses within wires are reduced strongly. For a rule of thumbs estimation, we assume a multiplication of today's nominal voltage of 12 V by a factor of 4 to 48 V. In a simplified view, neglecting minor effects like parasitic isolation losses, we can estimate the effect of the voltage shift on the electrical system using the following base equations:

(1) $P_{load} = V * I_{load}$

(2) $\Delta V_{wire} = R_{wire} * I_{wire}$

(3) $P_{wire}^{loss} = R_{wire} * I_{wire}^2$

with the power of a single load P_{load}, the voltage V and the load current I_{load} which equals the wire current I_{wire}, the wires resistance R_{wire}, ohmic power loss P^{loss}_{wire} and voltage drop ΔV_{wire}.

It is easy to tell, that an increase of the system voltage by a factor of 4 leads to an anti-proportional reduction by the same factor of wire currents (eq. 1) as well as voltage drop (eq. 2) and reduces the ohmic losses in the wire (eq. 3) by a factor of 16 (4^2). However, this is only the case if the wire resistance and thus the wire cross-section is kept the same, when moving to 48 V. Hence, the reduction of wire cross-sections, the improvement of voltage stability and reduction of ohmic losses cannot be maximized at the same time but must be balanced.

While such considerations can mostly be done analytically, the impact of wire inductances are often less obvious and easy to predict. The voltage drop across a connection wire ΔV_{wire} when the load current is changing is described by equation 4:

(4) $\Delta V_{wire} = L_{wire} * \frac{dI_{wire}}{dt}$

with the inductance of the wire L_{wire} and the current change rate or slew rate dI_{wire}/dt.

When combining Eq. 4 with Eq. 2 we can calculate the total voltage drop across a wire ΔV^{tot}_{wire} to:

(5) $\Delta V_{wire}^{tot} = L_{wire} * \frac{dI_{wire}}{dt} + R_{wire} * I_{wire}$

In the balancing act on how much to reduce wire cross-sections to gain maximal benefit from the higher voltage becomes more complex when considering the non-linear change of wire inductances and hence the effect on dynamic voltage drops across the wires. In vehicle measurements is has been shown[9], that using formular for the self-inductance L of a single wire in free space (Eq. 6) leads to an appropriate approximation:

(6) $L = 2l\left(\ln\left(\left(\frac{2l}{d}\right)\left(1+\sqrt{1+\left(\frac{d}{2l}\right)^2}\right)\right) - \sqrt{1+\left(\frac{d}{2l}\right)^2} + \frac{\mu}{4} + \left(\frac{d}{2l}\right)\right)$

with the length of the wire l, the diameter d and the relative permeability μ. In Fig. 5 the calculated inductance for a wire with a length of 1 meter is plotted for different cross-sections and compared with resistance values as they are given in an automotive wire manufacturer's specification.

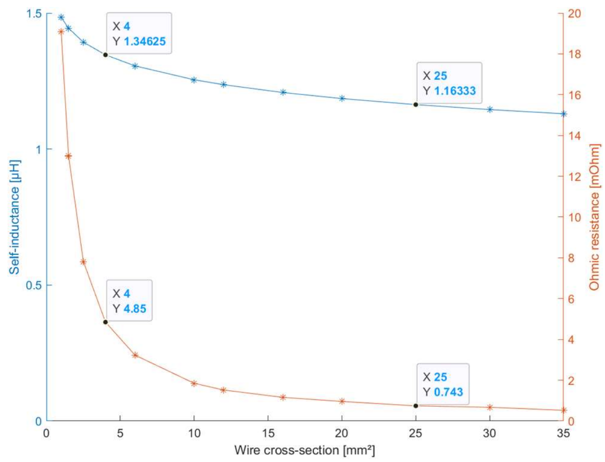

Figure 5: Wire self-inductance and ohmic resistance for commonly used cross-sections in the LV power supply net. Values for 25 mm² and 4 mm² are labelled, representing a reduction by factor 6.

Values for 25 mm² and 4 mm² are labelled, representing a reduction by factor 6 – a value that is discussed to minimize the cross-section while also respecting the thermal limits of the wire. The calculated inductance shows a moderate logarithmic increase towards lower cross-sections, while the resistance shows the expected anti-proportional (~1/x) dependency. An exemplary reduction of the cross-sections by 6, a value that is discussed to minimize the cross-section while also respecting the thermal limits of the wire, is showcased in the diagram with a step from 25 mm² to 4 mm². While the ohmic resistance is increased roughly by a factor of 6.5, the inductance just rises by a factor of 1.16.

Understanding the impact of reduced wire cross-sections on voltage dynamics in conjunction with the higher voltage levels is crucial for an adequate estimation of the benefits on the wiring harness. The left side of Figure 6 shows the result of a simulation for a dynamical load – a brake booster during an emergency braking event - in a realistic wiring setting which was parameterized according to vehicle measurements.

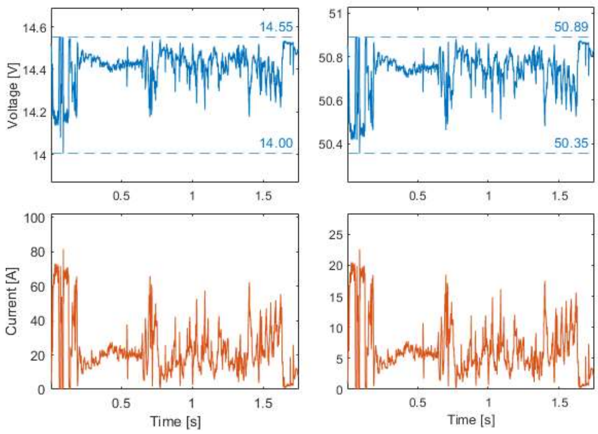

Figure 6: Measured current profile of a brake booster and simulated system voltage response in its original 12 V setting (left) and a prediction for 48 V (right) with reduced wire cross-section.

The break booster creates a high ripple current on the 12 V based LV power network in case of an ABS supported braking event (left column). On the right side the same load and use case is simulated with the same wire length but once more a reduced cross section by a factor of 6 for a setting adjusted to 48 V. The peak-to-peak voltage dynamic is almost identical despite the different wires. Considering the ~ 3.5 times higher voltage at 48 V this results in a reduced relative voltage dynamic by the same factor, while still respecting the thermal limitations due to the lower cross-section.

3.2. Error case – Power supply failure

Already on topology level some advantages or shortcomings of different solutions can be analyzed using simulation. To showcase such studies two generic system models for the previously introduced backbone and PDU centric supply topologies were built. To simplify the study and for an easier interpretation of architectural impact only one system voltage level (12 V) was used in the models. A realistic setting was chosen for the positioning of the power supplies and distribution components like PDU and ZCs (ZC1 in the rear, ZC2 front right, ZC3 front left and ZC4 in front, see also Fig. 2), while loads where grouped into low power basic loads (BASIC), non-safety loads (QM) and safety loads (ASIL).

The topologies show an almost identical setup using the four ZCs to distribute the power to assigned groups of loads of the three types. The supply architecture however deviates in how the ZCs are supplied and linked and where the power sources are connected to (see Fig. 3). Furthermore, both supply nets feature safety mechanisms like the fast semi-conductor-based shut-off of faulted loads (short circuit) and a power management functionality allowing the drop-off of non-safety critical loads in system overload conditions. The power sources are modelled as a fast DCDC converter with 3.6 kW peak power and a high current slew rate of 300 A/ms and a 40 Ah lithium-ion battery featuring high power cells using an NMC chemistry.

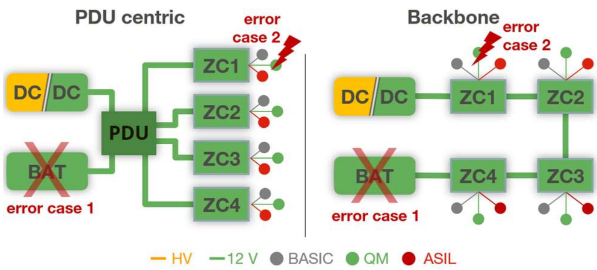

Figure 7: 12 V based PDU centric and backbone architectures with different types of load groups connected to the ZCs and imposed error cases battery malfunction (1) and short circuit (2).

In a first error case study (see Fig. 7), both systems are in a very high load condition (~500 A) with the DCDC converter in power limitation and the LV battery stabilizing the system voltage. An error is super-imposed to the scenario emulating a battery failure, e.g., a malfunction of the battery contactor.

Fig. 8 shows the result of such a simulation for the PDU centric topology and visualizes the impact of the safety mechanisms on the system, especially the stable supply of safety loads. The corresponding results for the backbone architecture are displayed in Fig. 9. On the left side of both figures the staggered drop-off of QM loads connected to different ZCs, triggered after 100 µs at a voltage at the ZC below 10 V, can be seen. The main differences are a drop-off of 3 loads instead of 2 for the PDU centric solution with a late drop of the third load, leading to a longer supply with less than 10 V (~3 ms compared to ~0.5 ms) at the ASIL loads, also connected to the ZCs (see right sides of Fig. 8 and Fig. 9). Hence, in this specific scenario and the chosen physical and control parameters the backbone architecture seems to cope better and reacts faster to the loss of one of the main power sources.

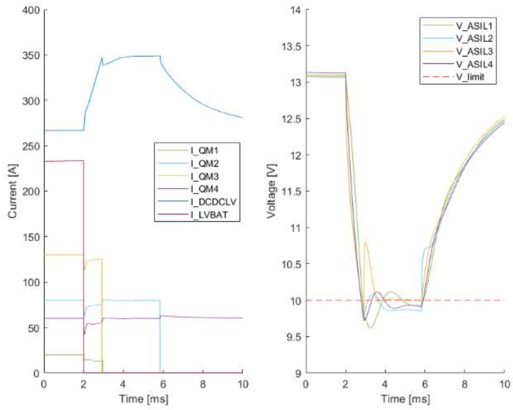

Figure 8: Result of a system simulation in a 12 V based PDU centric architecture in an overload situation and battery failure.

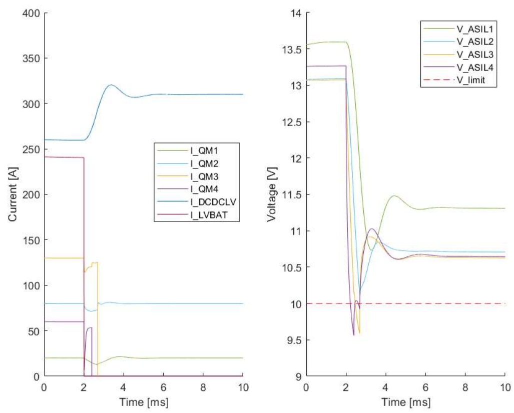

Figure 9: Result of a system simulation in a 12 V based backbone architecture in an overload situation and battery failure.

3.3. Error case – Short circuit at QM load

In a second use case study, a moderate overall power demand was considered (~60 A) and a low ohmic (10 mOhm) short circuit at a non-safety load connected to ZC1 was super-imposed. The load switches within the ZC were configured to disconnect faulted loads within 100 µs of overcurrent, with the current limit set to 200 A in this instant. The simulation results for the PDU centric and the backbone architecture can be seen in Fig. 10 and Fig. 11 respectively.

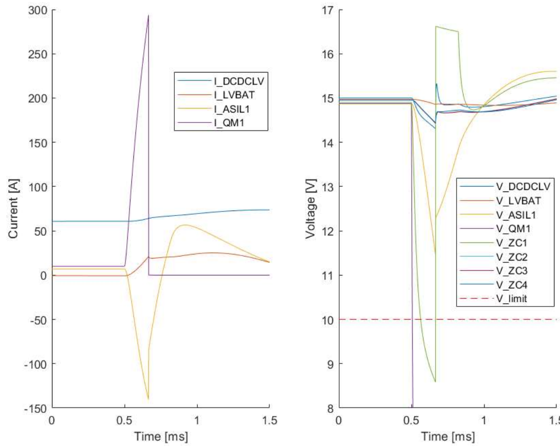

Figure 10: Currents for supplies, faulted and safety loads (left), and voltages (right) in a short circuit scenario for a 12 V based PDU centric architecture.

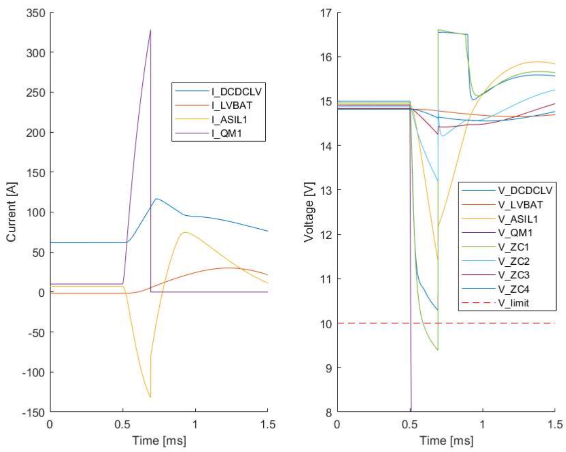

Figure 11: Currents for supplies, faulted and safety loads (left), and system voltages (right) in a short circuit scenario for a 12 V based backbone architecture.

The current at the short-circuited load QM1 (purple line) is increasing rapidly, initially fed by buffer capacitances of the other loads connected to the same ZC, like the large DC-link capacitor considered in the load ASIL1 (negative yellow curve). As the voltage in the network drops, the current input of the DCDC converter (blue) and the LV battery (red) increases, with clear differences between the two architectures, due to the varying supply paths. Looking at the system voltages (right sides of Fig. 10 and Fig.11) it can be seen that the voltage in ZC1 drops below 10 V until the faulted load is disconnected and then runs into an overvoltage due to the high currents induced by the inductances of the connection wires leading to the ZC. Any overvoltage in the ZCs is clamped at 16.5 V in the model, as can be seen for the green

curve in the voltage plots (right sides). Due to the higher DCDC currents seen in the backbone architecture before the faulted load is dropped a clamped overvoltage event can also be observed at the DCDC (blue curve in Fig. 11). The peak current reached at the short circuit is slightly lower in the PDU centric architecture, where the additional stage of the PDU in the power path acts as a buffer and delay for the fault propagation in the system.
In both architectures the voltage at the connected safety load V_ASIL1 (yellow curves on the right side) stays above 10 V, since it is buffered by a large DC link capacitance.

These examples show that there will not be a simple technical answer to the question of the best supply architecture, but that each configuration must be tested and analyzed in all relevant scenarios and conditions to find the best suited solution. System simulation offers an efficient method to perform a large number of tests and parameter studies and apply even the most extreme conditions to a study object without the need for a costly sample buildup or elaborate measurement equipment. Especially for the vehicle power supply network with it many interconnected loads and power sources and the high number of factors impacting the electrical behavior of the network, it can be of great use already in a very early development phase.

4. CONCLUSIONS

Major changes in the way that power on low voltage level is generated and distributed are necessary to facilitate new and demanding vehicle functions like autonomous driving. At the same time, the historically grown structure of the wiring harness needs to be disentangled, made more efficient and easier to manufacture. New zonal vehicle architectures combining a 48 V based power distribution with a localized sub-distribution of the power on multiple voltage levels offer a wide range of advantages and enable a step-by-step transition of loads from 12 V, making them an interesting option for OEMs struggling with legacy effects.

Finding an optimal configuration that takes the various requirements into account is a crucial task, that demands an adequate exploration of the large solution space of potential architectures. Since the components needed to realize this new generation of the vehicle power supply networks and their respective requirements strongly depend on the selected configuration, a close collaboration between supplier base and OEM is needed, already starting at vehicle architecture level. It is only through a joined effort that the cycle of low supply and demand of components for 48 V can be overcome, to make the introduction into the mass market successful. The selection of the most suitable solutions will be highly dependent on the individual targets of the OEMs, and a detailed comparison of the concepts is needed.

Due to the complexity and the many interrelations of such large networks, system simulation is of crucial importance for the technical aspects of this evaluation. Lastly, the currently led discussion regarding the legal framework for the different low voltage levels in the vehicle (12 V, 24 V and 48 V) may lead to the introduction of a new ISO standard, potentially simplifying and bolstering an adoption of 48 V as the main LV voltage level in passenger vehicles.

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