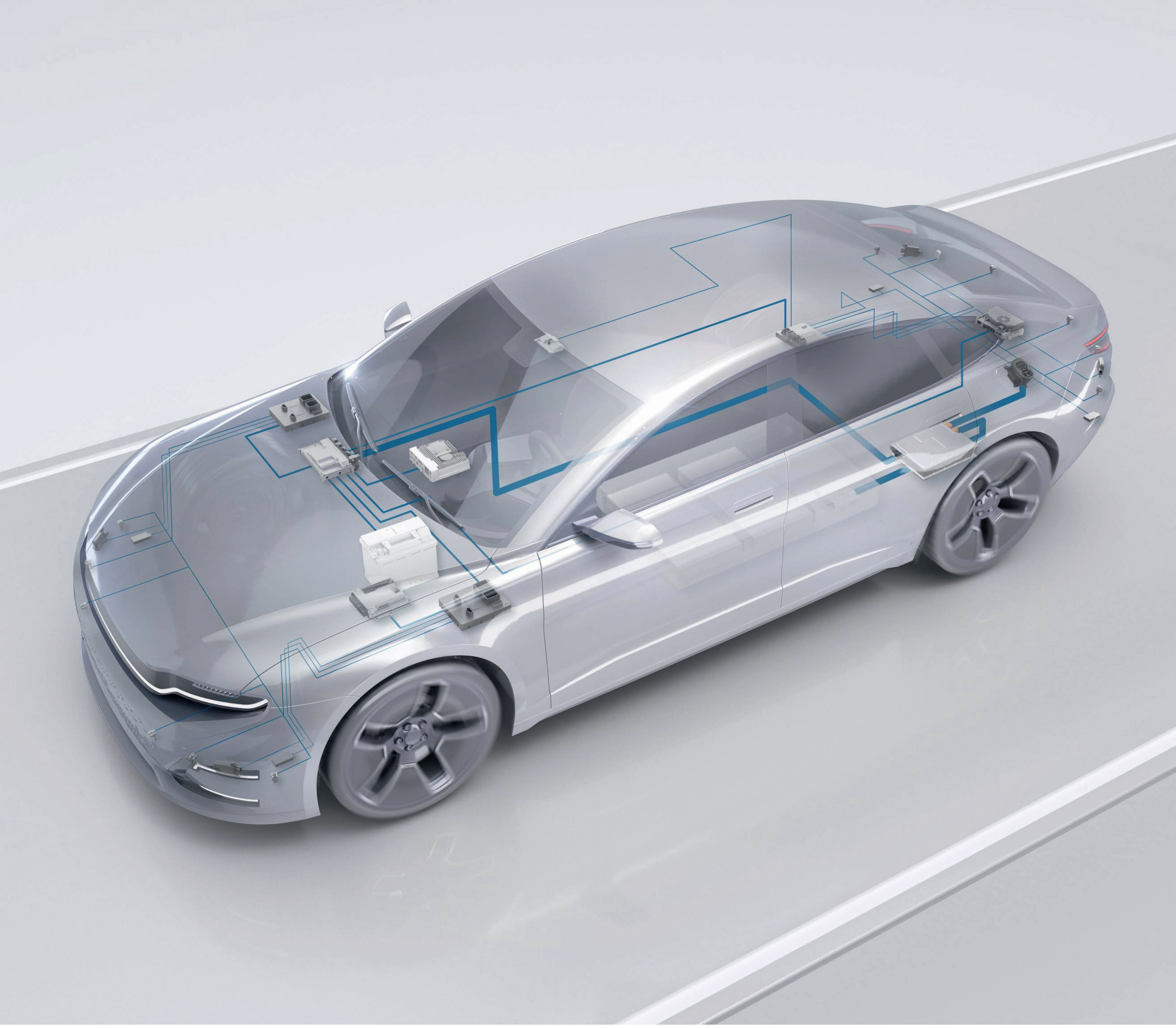

Whitepaper

Gear up vehicle powernets for future mobility

Invented for life

BOSCH

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01
Overview

With the current automotive megatrends like the software-defined vehicle on the horizon, the need for advancing the vehicle's technical infrastructure is becoming increasingly important. New reliable and safe power supply solutions are the foundation for enabling higher driving automation levels, introducing new technology platforms, e.g., for x-by-wire systems, and responding to the increasing power demand of subsystems such as automated driving, driver assistance, and infotainment.

Additionally, the transition to purely electric E/E architectures is providing new opportunities for cost-efficient architectures by taking advantage of the ubiquitous high-voltage power supply.

There are numerous factors to consider when overhauling the powernet for future mobility. In this whitepaper, we focus on four of them:

Safe power supply solutions

We will look at recent advances in safe power supply solutions and their design considerations as derived from the ISO 26262 norm (ISO, 2018) and further elaborated through VDA recommendation 450 (VDA, 2023).

Change from 12 V to 48 V

We summarize the benefits and potential pitfalls of introducing 48 volts to vehicle systems as an additional voltage level.

Future of low-voltage powernets

We give an overview of safe power supplies and how their use of low-voltage batteries is optimized.

Simulation-based system design

We discuss and give examples to show the pivotal role of simulations for practical systems engineering in these increasingly complex environments.

02
Introduction

For decades, engineers have been optimizing powernet designs to ensure the availability of the power supply, even in harsh environmental conditions, and to reduce the total system costs. These designs were then extended for efficiency through new design options in relevant subsystems such as start-stop and recuperative braking.
At the same time, several standard patterns for safety-relevant parts were derived.
In conventional vehicles with combustion engines, the safety-critical and post-crash relevant parts of the system are often kept available by local reserve solutions like backup batteries, or by using alternative means (e.g., a hydraulic fallback for brakes).
Initially, these original designs have been carried over into battery-electric vehicle architectures mostly unchanged.

Innovative functions challenge the energy supply

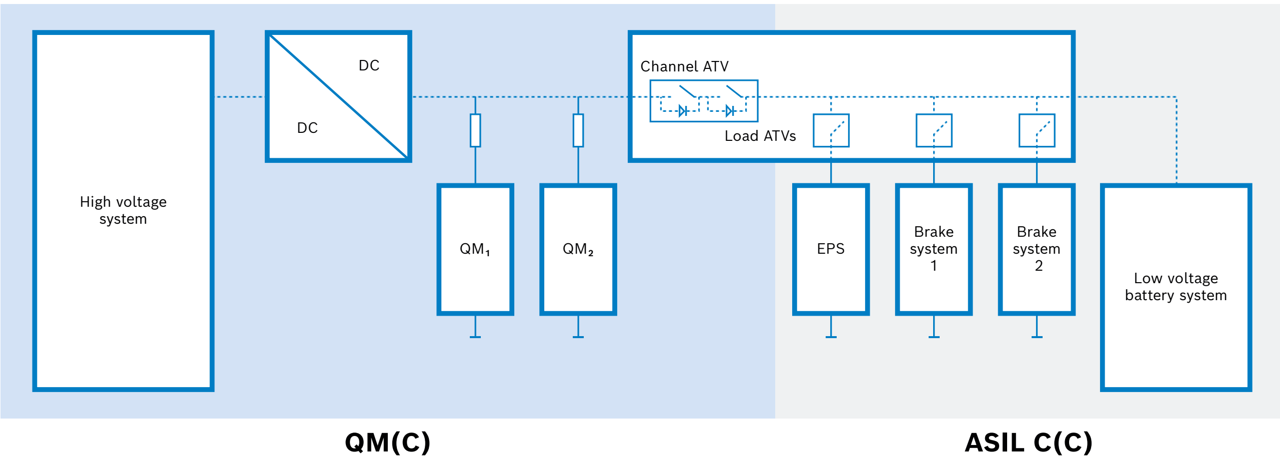
However, the solutions mentioned above are becoming increasingly limiting. In particular, new high-power functions with increased power supply availability requirements, e.g., steer-by-wire and brake-by-wire, cannot be integrated economically. Additionally, conventional powernet architectures may not suffice for the very high safety-related availability requirements where a loss of power supply is unacceptable for critical functions that exclusively depend on an electrical power supply.

From the main cause of downtime to a pillar of availability

Even beyond safety requirements, the powernet has always been a critical design element of the vehicle E/E architecture, with more than 50% of all vehicle breakdowns being accounted to powernet failures, of which over 40% are due to a failing low-voltage battery (ADAC, 2021). With an increasing number of electrical parts in the vehicle, this amount has increased further.
A reliable powernet is thus vital for the perceived overall product quality and reliability of a vehicle. Thus, safety and quality need to go hand in hand when it comes to defining new architectural solutions for the low-voltage vehicle power supply.

03
Safe disconnect switches protect critical loads

Conventional (melting) fuses serve the primary purpose of protecting the wiring harness against damage. They generally do not react fast enough to prevent undervoltages in other components, which can lead to critical brownouts of safety-critical parts. That is why automotive manufacturers are progressively introducing safe disconnect semiconductor switches, which offer unprecedented reaction times to malfunctioning and extended monitoring. Using the language of VDA recommendation 450 (VDA, 2023) (see Section 5), they are generally integrated as active separating and connecting elements ("Aktives Trenn- und Verbindungselement", ATV).



ATV: Active separating and connecting element
DC: Direct current
EPS: Electric power steering
ASIL: Automotive safety integrity level
QM: Quality managed (ASIL Level)

Figure 1: Active separating and connecting elements ensure reliable supply to safety-critical loads.

Figure 1 depicts the concept of a "channel" ATV using the example of a power supply system for steering and braking loads with safety-related availability requirements up to ASIL C. The left-hand QM(C) supply channel drives all low-voltage (LV) loads from a DC/DC converter via the high-voltage (HV) system. During regular operation, the switches remain closed and energy flows through the ATV towards the safety loads. In case of a malfunction of a QM load such as a short circuit to ground, the ATV disconnects this channel.

After separation, power for the safety loads is provided exclusively by an LV battery. To ensure the availability of this backup path, the battery is constantly monitored for aging, state of charge, and other potential performance issues. Safety loads are furthermore protected by individual ATVs.

Nowadays, the ATV is preferably not implemented independently but integrated into a sophisticated power distribution device. Taking the example of the Bosch powernet guardian (Bosch, 2023), this enables manufacturers to holistically manage the power supply paths of the vehicle during its entire lifetime and increase diagnostic coverage. In Table 1 we provide a small overview of the features of such an integrated device that gives granular control over energy flows to subsystems and loads.

Safe supply	Fault avoidance and fault tolerance measures to ensure the power supply of the connected loads
Safe disconnect for self-protection and short-circuit isolation	Over-current and over-temperature self-protection if the load exceeds specified current-time thresholds Over-current disconnection for short-circuit isolation Load shedding for overload situations and fault handling
Safe disconnect for under-/overvoltage separation	Voltage-time thresholds for ensuring a stable power supply
Fast reconnect	Fast reconnection of a path after preventive disconnect due to overheating hazards from reverse currents
Sleep mode	Continuous power supply with minimum quiescent current consumption Fast wake-up triggered by load current draw
Precharging of connected load or power supply channel	Current-limited charge-up of load branches and overall power supply system
Wiring harness protection	Disconnection of load paths to avoid wiring harness overheating
Wiring harness diagnosis	Monitoring of wiring resistance
Terminal control	External control capability to open/close load outputs
Reverse polarity protection	Disconnection of reversed battery inputs
Diagnostic services	Access to operation information, diagnostics, and calibration from diagnostics testers
Parameter storage and adaption	Calibration and monitoring interface for development

Table 1: Excerpt feature set of a power distribution device such as the Bosch powernet guardian.

The appealing feature set of intelligent power distribution devices is driving their adoption into mainstream E/E architectures. Automotive manufacturers are moving towards full-fledged electronic switching solutions, see Figure 2, with the introduction of their new vehicle-centralized architectures. With fewer but high-performance vehicle computers and an intermediate zonal layer for sub-distribution, power distribution devices have become commercially attractive. To reduce overall system costs, some automotive manufacturers have not yet fully moved to electronic fuses. Instead, they are keeping some loads that have lower feature requirements protected via conventional fuses. However, we expect the trend towards the primary use of electronic fuses to continue with further consolidation in the overall E/E architectures. Apart from better controllability, this also allows the option to move powernet elements to non-accessible installation spaces, or to replace a central channel ATV with individually monitored load paths.

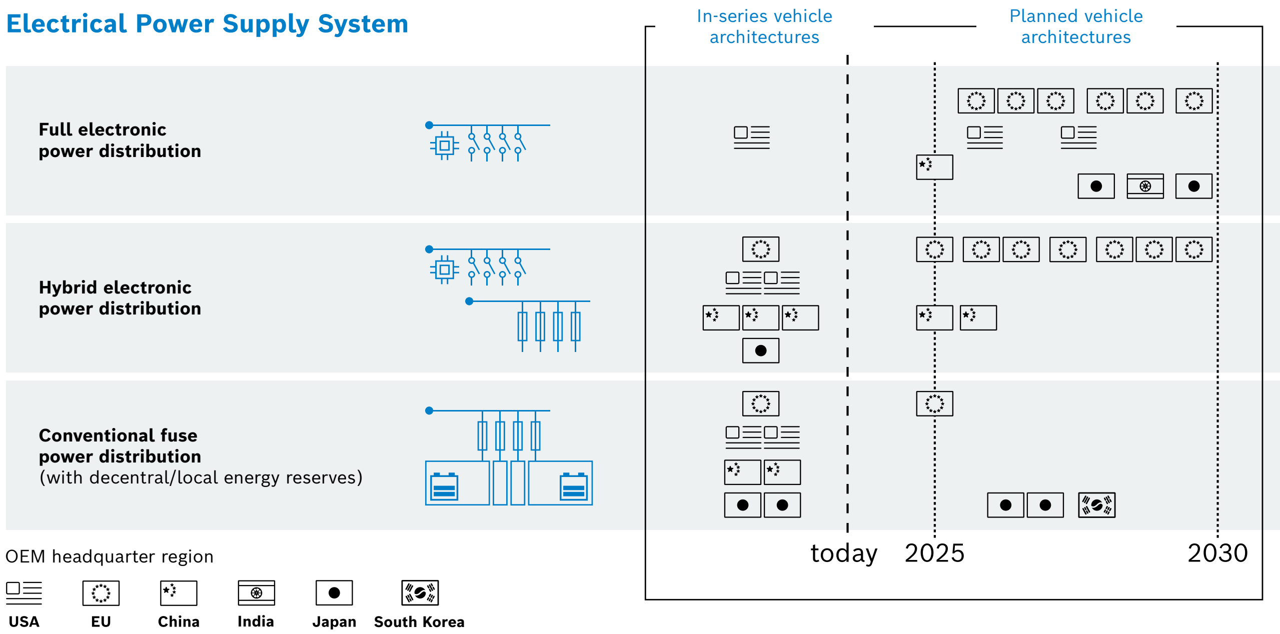


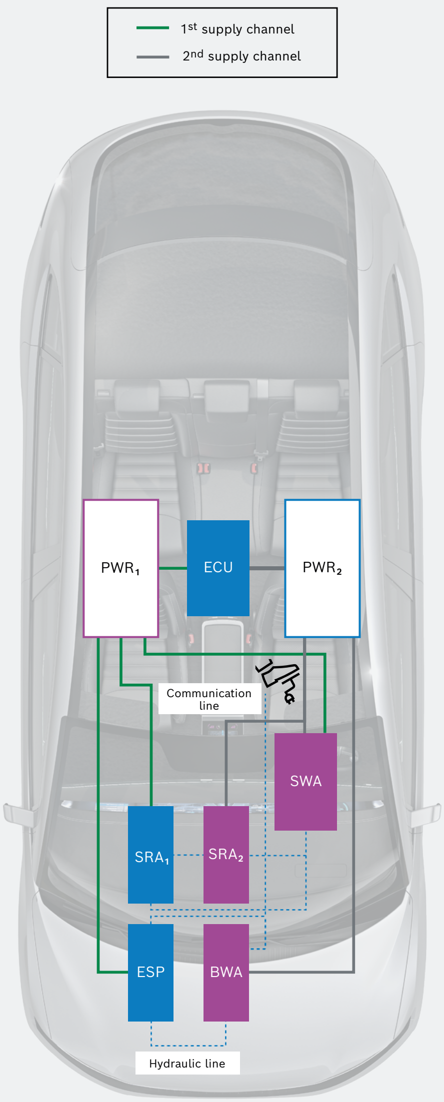
Figure 2: Bringing more intelligence to the powernet is a general trend.

04
Downsizing, alternatives and removing of low-voltage batteries

Steer-by-wire and brake-by-wire systems are gradually replacing the mechanical/hydraulic path from the driver to the steering rack and brakes with fully electronic solutions. This imposes high safety and fail-operational requirements onto the powernet because failures cannot be compensated for by non-electrical force transmission. Furthermore, end users naturally expect the same overall availability as with conventional systems. In such setups, safety and non-safety related availability in the powernet needs to be guaranteed, usually by introducing more redundancy. In addition to that, equally relevant technical recommendations and norms, as well as legal requirements, reduce the solution space of such setups.

In systems such as the one shown in Figure 3, the power supply path is subject to safety goals up to ASIL D. The implementation generally decomposes this into requirements for individual and independent supply paths towards the critical loads, e.g., towards the electronic stability program ECU (ESP) and the by-wire actuator (BWA). Nevertheless, this approach is universal, i.e., it applies to other vehicle systems with high-availability power supply needs.

Various options exist for creating such paths with the respective ASIL rating and mutual independence. The most straightforward solution duplicates the energy reserves and active sources, including the power distributor. A subsequent downsizing of the battery capacity and sometimes also the



PWR: Power supply system
ECU: Electronic control unit
SWA: Steering wheel actuator
SRA: Steering rack actuator
ESP: Electronic stability program
BWA: By-wire actuator

Figure 3: Steering and brake-by-wire system with redundant power supply paths.

removal of battery sources are often optimization goals in order to improve vehicle-level reliability (battery failures are a common reason for breakdowns, see above) and reduce vehicle weight, costs, and maintenance needs.
In the following, we focus on these optimization options.

4.1 Moving from low-voltage lead-acid to lithium-ion batteries and downsizing their capacity

The 12 V lead-acid battery has been the workhorse of the low-voltage powernet for many years. It is used for many purposes such as cranking the engine of a combustion engine vehicle, supplying quiescent current, and acting as a buffering element in combination with the alternator. Although the lead-acid battery is prone to aging due to its cycling and partial charging (sometimes also to mechanical faults and water loss) it is very robust in operation, e.g., regarding its tolerance towards overvoltage peaks, charging at low temperatures, etc. Additionally, it is a very cost-effective solution. However, with (planned) environmental regulations and other disadvantageous properties such as its high weight, high failure rates, and lifetimes of only a few years, there is a common wish to replace lead-acid with lithium-ion batteries in the future.

While lead acid batteries can only be used when their state of charge is between 50 and 100 percent, lithium-ion batteries can be used almost over the entire capacity range. This fact, as well as other beneficial factors (e.g., a lower internal resistance), allows for a significant reduction of the overall capacity of these batteries, compared to their lead-acid counterparts. For instance, lead-acid 12 V batteries in EVs typically store around 30 – 60 Ah, whereas lithium-ion 12 V batteries can even be downsized below 10 Ah. At the cell chemistry level, lithium-ferrite-phosphorus (LFP) and nickel-manganese-cobalt (NMC) cells configured as four single cells in series (4s1p), currently show the potential to become the typical 12 V implementation. Such batteries usually come with their own battery management system (BMS), including cell monitoring and a semiconductor battery main switch.

However, lithium-ion batteries introduce their own new challenges for the powernet design. Taking the example of an NMC-based battery in 4s1p cell configuration, the nominal operating voltage level will increase from approximately 12.5 V to 14 – 15.5 V for open circuit and from 14 – 15 V to 15 – 17 V for the charging voltage. Other system components hence need to be adapted. Moreover, due to the smaller battery capacity, the quiescent current in the parked state of the vehicle must be reduced. Otherwise, a need for re-charging from the high-voltage battery during parking arises. This not only affects the powernet architecture but also impacts functional allocation and the communication network architecture, e.g., regarding the use of partial networking. Furthermore, the capability to support and buffer high current peaks is reduced and, in some cases, the voltage converters need to be adapted to accept more peak currents. As an alternative, capacitors can be used to support the voltage converters. The transition to lithium-ion batteries is therefore no “drop-in replacement”.

4.2 Using the high-voltage battery and voltage converter for safe low-voltage supply without low-voltage batteries

As mentioned above, the low-voltage battery is still the main root cause of vehicle breakdowns, even in modern vehicles. The introduction of fully electric vehicle platforms, however, allows the opportunity to consider removing the low-voltage batteries entirely in order to fully rely on the high-voltage battery. As expected, there is a high interest in exploring this path.

Our current observation is that for the redundant two-channel powernet architec tures needed for high availability scenarios, the low-voltage battery will be removed from one of the two channels in a first step, as depicted in Figure 4, center option. In this case, the channel lacking the low-voltage battery will be supplied from the high-voltage battery via a separate voltage converter. In this configuration, all loads needed during parking will be preferably moved to the channel that is still supplied from a low-voltage battery.

However, even that first step will require some changes in the high-voltage powernet and the voltage converter for that channel. Typically, each of the two low voltage channels will have an ASIL B(D) rating on its availability requirement. This implies that the high-voltage battery, the voltage converter for that channel, and the high-voltage power distribution will also get ASIL B(D) rated availability requirements. In addition to that, functional requirements must also be adapted. For instance, the voltage converter must support a higher current dynamic (up to 400 A/ms). Alternatively, other measures to deal with current feedback from components, such as steering systems, need to be implemented.

On the high-voltage side, unintended interference between QM-rated loads in the high-voltage powernet and the high-voltage battery and voltage converter need to be considered and, if necessary, prevented. Furthermore, the ASIL B(D) rated voltage converter may be connected directly to the high-voltage battery terminals, i.e., before the battery main contactor switches. This voltage converter may technically beneficially be integrated into the high-voltage battery enclosure to avoid access to unprotected high-voltage wires and better support always-on needs.

Elimination of the LV battery in one of two redundant power supply channels

channelsA more radical option is to completely remove all low-voltage batteries in both channels (see Figure 4, right option). This requires further extensive adaptations. Both low-voltage channels will hand down their ASIL B(D) rated availability requirement to the high-voltage battery supply. That means that in a single high-voltage system scenario the high-voltage battery would inherit an ASIL D rating. It is more practical to assume that the high-voltage powernet will instead be split up into two redundant high-voltage paths with two battery packs, separate high voltage power distribution, and separate voltage converters. Naturaly, dependent failures between the two high-voltage paths as well as systematic failures need to be prevented.

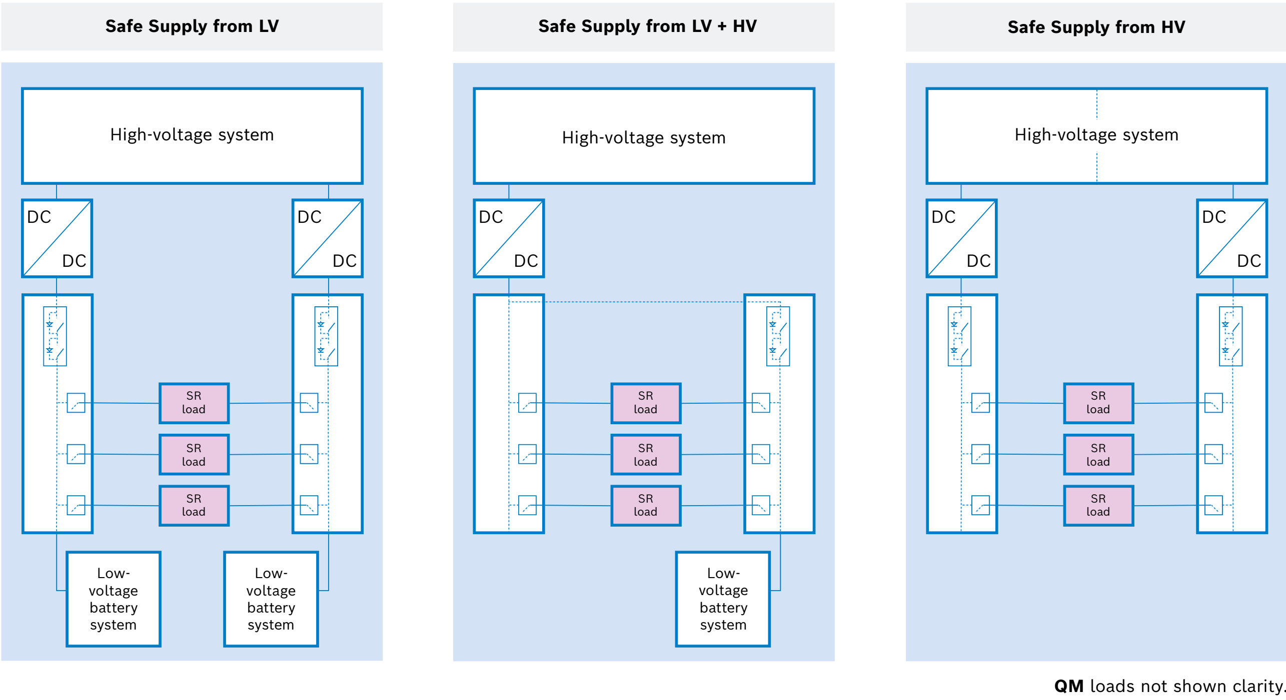


Figure 4: Options for safe supply with different energy sources/reserves.

Complete elimination of all LV batteries

An additional challenge is created by current peaks that must be handled by other means in low-voltage batteryless paths. The voltage converters need to be designed to cover all power and current demands, including all peaks. Introducing capacitors into the low-voltage powernet to support the voltage converter could be a helpful measure to support voltage level smoothing, but with-out the capability to store large amounts of energy. Furthermore, quiescent current during parking needs to be provided via voltage converters. Due to big main voltage converters generally having a low efficiency at low power output, it is likely more effective to use one or two additional low-power voltage converters for the quiescent current supply.

In conclusion, all benefits of this radical option (component cost savings, weight and space savings, improved vehicle availability) need to be carefully compared with the costs for enabling the high voltage powernet. Nevertheless, it can be attractive for vehicle platforms that generally need a redundant two-channel low-voltage powernet (autonomous driving-by-default vehicles, by-wire solutions with high take rates, etc.) and that contain a high-voltage battery, split up into two separate modules, e.g., with 2x400 V battery packs for 800 V vehicles.

05
Simplification of powernet analyses with VDA 450

The development of safety concepts for the power supply system has been inhomogeneous in the past. Safety standards like the ISO 26262 norm have been applied to the power supply system very differently, which led to a great variance in the quality, availability, and safety of power supply systems.

With the emergence of steer-by-wire and brake-by-wire functions, as well as automated driving functions that require a reliable, fail-active power supply, the development of power supply systems has gained more prominence in safety engineering.

The VDA association acknowledged the need for clarification and guidance and hosted a working group tasked with providing a well-aligned development method for power supply systems that is compliant with safety standards (ISO 26262 2nd ed.) as well as legal requirements (e.g., UN ECE R13(H), GB 21670 and FMVSS for braking, UN ECE R79 and GB 17675 for steering, UN ECE R157 for automated lane keeping).

Conformity to safety standards is an important quality of the power supply system. For some vehicle functions, compliance with ISO 26262 or GB/T 34590 is already required for homologation (e.g., for automated lane keeping systems via UN ECE R157, BEV traction batteries via GB 38031-2020). Therefore, compliance with ISO 26262 has been a core element for the VDA working group.

With the 2nd edition of ISO 26262, new options for item definitions have become available. This includes items that perform only part of a function on the vehicle level. Naturally, the power supply system falls into this category and the VDA 450 working group based its first development method on the premise that the power supply system is defined as such an item. This brings some advantages. For example, the power supply system can be developed to fulfil its own set of target values regarding random hardware faults (PMHF, SPFM, LFM). The target values for the power supply system in this scenario are independent of other functions like steering and braking, which largely reduces complexity and interdependency in the development phase.

With the release of German VDA recommendation 450 for automated driving functions, the development of respective safe power supply systems has become significantly easier. It is expected to become a state-of-art reference for other global norms and implementations. The recommendation covers general design rules for the power supply system and its elements. It uses a top-down approach to derive requirements that need to be fulfilled according to the respective norms. The recommendation collects enhancements and best practices, e.g., for budgeting, fault handling, emergency operation tolerance time intervals, and a new and improved terminal nomenclature with safety properties. For practitioners, it further contains comprehensive lists for checking external and internal conditions that may compromise the freedom of interference.

The VDA recommendation 450 was developed by leading industry experts, including many OEMs and Tier 1s such as Bosch. Its usefulness for real-world powernet designs is proven by application examples to reference topologies and it may be extended to systems beyond automated driving, such as the aforementioned x-by-wire solutions. Its value for future architectures is thus indisputable.

06
48 volts in low-voltage power supply

Infotainment and ADAS features lead to an increasing power demand in the low-voltage power supply network. With more computing performance, larger displays and comfort functions ("living space on wheels") as well as a safety-capable power supply for automated driving, the average vehicle power consumption is expected to reach 5 – 6 kilowatts by the end of the decade. Due to the ongoing centralization, more energy must be transferred into fewer ECUs, which results in larger wire gauges and bigger semiconductor switches to carry the required currents. From a power distribution perspective, a request to raise the low-voltage level for the power supply is thus natural, as it allows for the reduction of the overall wiring harness weight, effort and cost for semiconductor switches. The recent announcement of Tesla (Tesla, 2023) to quadruple their low-voltage level to 48 V was therefore expected. Given that above 60 V auxiliary requirements like additional maintenance safety precautions come into play for vehicle subsystems, this is the most straightforward voltage level to select.

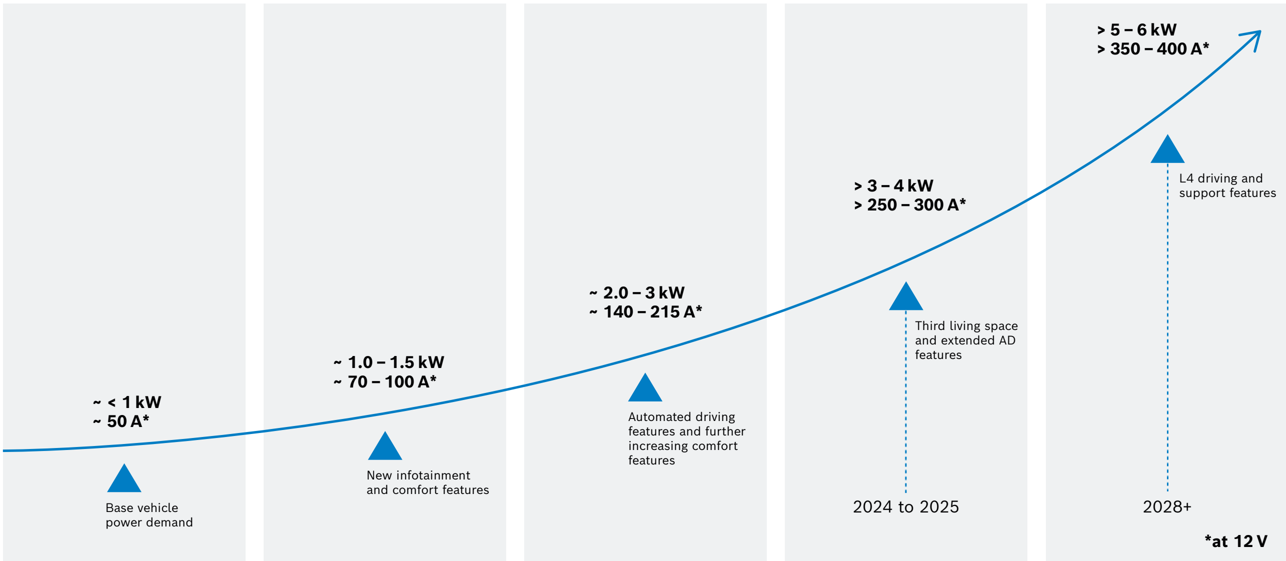


Figure 5: Evolution of power needs in low-voltage powernets.

The biggest challenge in the transition to 48 V is the significant legacy in current vehicle architectures. 12 V has been the main voltage level since the 1960s; therefore, virtually all vehicle components are optimized for it. There are a few notable exceptions, e.g., in the power supply for mild hybrids and active suspension. However, these currently form only a small island within the overall vehicle powernet.

Classification of consumer type

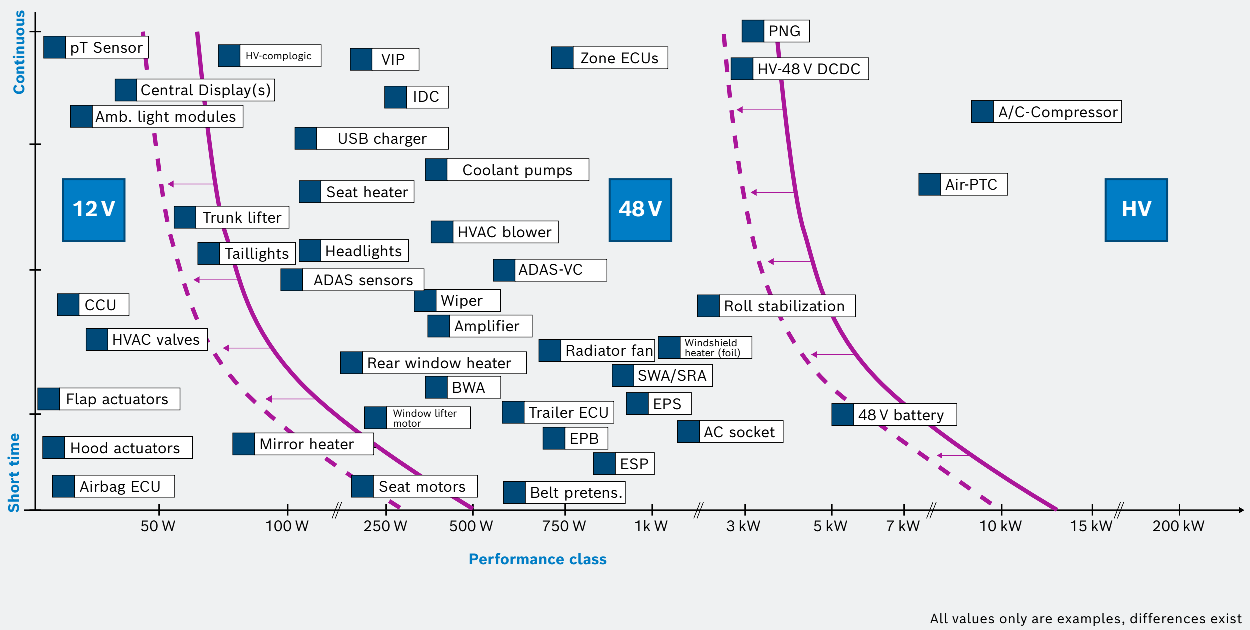


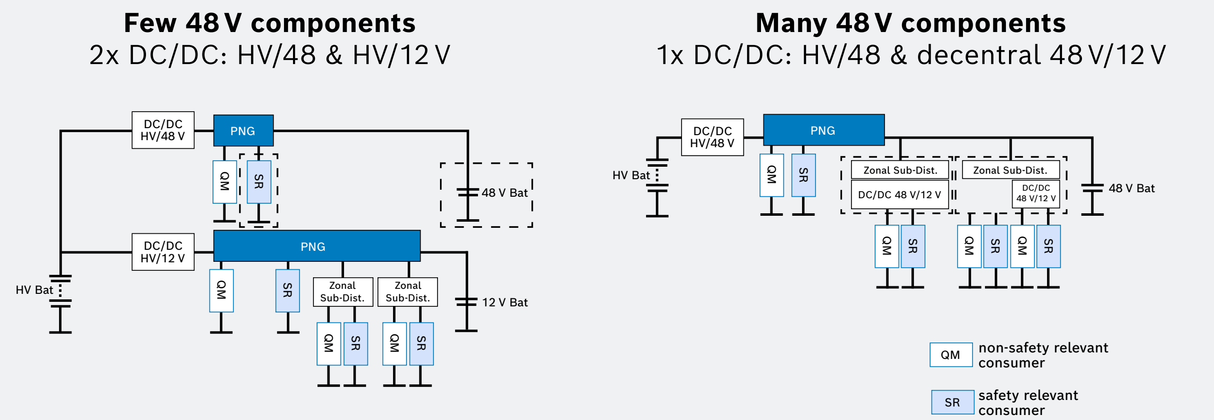
Figure 6: 48 V aims to hit a sweet spot between the migration of high-power loads to HV and the reduced marginal benefits of a shift to 48 V for low-power components. (Illustrative example, needs to be assessed individually in existing architectures). The limit values shift over time due to technological and cost developments (dashed lines).

Together with Tier 1 suppliers like Bosch, automotive manufacturers are assessing potential migration scenarios carefully and with a focus on individual loads and the overall system total cost of ownership (system TCO). However, as usual in E/E architecture analyses, there is no one-size-fits-all solution. From our current analyses, we see that 48 V will not entirely replace 12 V as the new low-voltage level of cars in the short term but may, for some components, become a third option between the current standard of 12 V and high voltage.

While some OEMs will stick entirely to 12 V, or an increased voltage beyond 16 V, some will follow a step-by-step migration to 48 V. Universal fast and comprehensive migrations from 12 V to 48 V are still under elaboration. Because there are no native 48 V components readily available, a cost adder initially not compensated for by wiring harness, fuse cost reductions and efficiency gains is expected. In the long term, despite decreasing the cost of 48 V components, it will also become important to look for sweet spots for 48 V components (see Figure 6) because moving components to the high-voltage powernet instead could become a viable alternative. For low-power loads, the achievable gains in terms of reducing the costs of the wiring harness and increased efficiency are lower than the component cost adders for 48 V. In such cases, the overall system TCO drives the decision, i.e., whether to locally convert 48 V down to 12 V for small legacy devices or move these devices to 48 V.

Due to the introduction of the additional voltage level the additional infrastructure cost varies greatly. Depending on the number of 48 V components and the availability of a power sub-distribution layer (zonal architecture), different powernet architectures are better suited, see Figure 7.

For some reference architectures we find that the cost benefits from 48 V are realized due to a smaller overall number of ECUs and the stringent implementation of a zonal architecture with power sub-distribution. For an evolution from other architectures, the tipping points for a necessary change in the powernet architecture must be determined carefully. In conclusion, 48 V is not a simple drop-in replacement for the established 12 V solutions. Still, it may gain more commercial attractiveness with a better availability of components and the overall evolution of powernet designs.



+ reduce impact on existing 12 V components
+ focus on high power consumers first
+ optimization potential: remove 48 V battery

– two HV/LV pwoer converter
– energy storage on each voltage level might be required

+ energy storage on 12 V is substituted w/ decentral converters
+ central HV/LV converter

– requires a progressive migration strategy to reduce power demand of decentral 48 V/12 V converters

Figure 7: The amount of 48 V components and planned sub-distribution structure determine the design of the three-level powernet.

07
Simulations for safety verification and reliability assessment

Besides supporting the use of simulations to design the powernet and components, ISO 26262 highly recommends carrying out simulations to verify the absence of unreasonable risk in the powernet (ISO, 2018). Analogous to physical fault injection tests, a simulation environment may be employed to check the correct implementation, effectiveness, and performance as well as accuracy of the required safety measures.

In addition to that, over the past years the value of simulations has further increased beyond safety argumentations because of the complexity upsurge in powernet designs and the increasing number of variants. Since a costly physical setup for test scenarios can easily become prohibitive for evaluating design alternatives, simulations are used instead to get early feedback and achieve a high test coverage even with large numbers of variants.

Different questions require different simulation methods

In Figure 8 we show a basic clustering of the types of simulations that we usually conduct as part of powernet architecture design activities. Beyond simple energetic simulations (supply capabilities, energy reserve keep-up capabilities, etc.), we analyze the voltage stability of the powernet in all possible use cases of nominal operation as well as in various fault scenarios. With the increased use of high-speed communication, sensitive vehicle computers, and many high-frequency switched power electronics in vehicles the evaluation of transient effects, voltage ripple and interaction between HV and LV networks is becoming more important. As mentioned above, the outputs of these simulations are highly useful for powernet and component design, e.g., to optimize battery dimensioning. Simulations can also be used for verification and validation of the powernet design and functional safety concept, the interaction of the physical powernet with SW functions (e.g., electric energy management or diagnosis), and for reliability analyses. Since simulations are easy to scale, they are also highly useful for comparisons of different powernet architectures and possible solutions as well as parameter variations of component properties or environmental input conditions (temperature, mission profiles, etc.), to name a few.

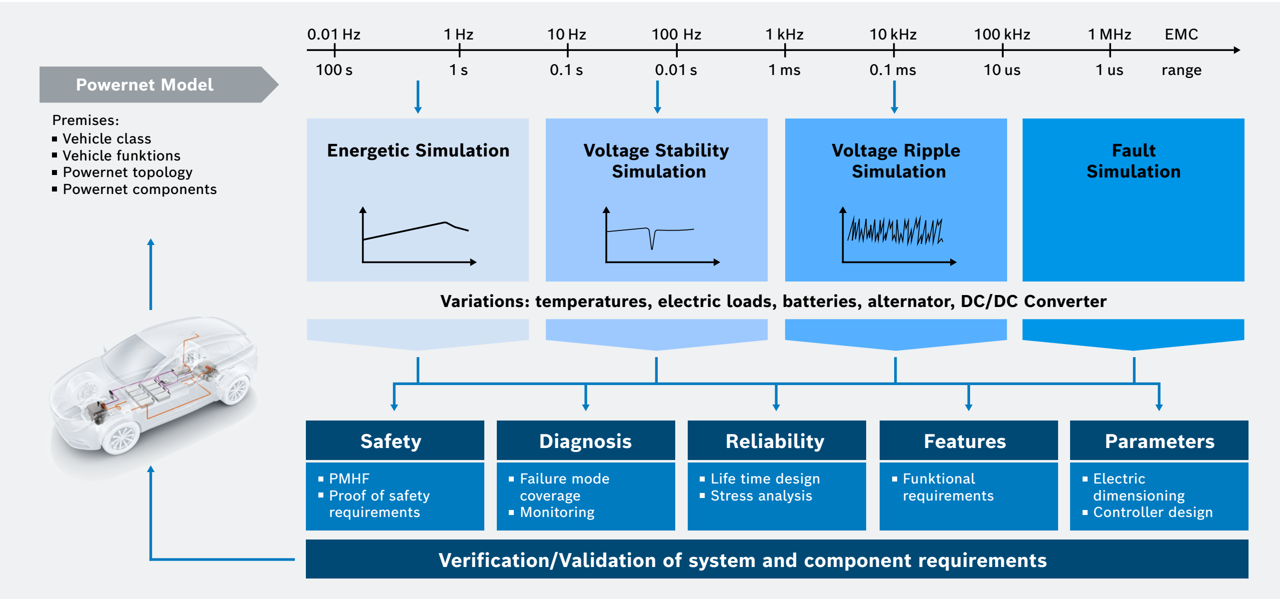


Figure 8: Simulations support safety verification as well as functional and reliability analyses to evaluate architectural design decisions early on.

Support for DC/DC converter development through powernet simulations

For a simple example of a typical simulation task, we show the simulation results and measurements of a DC/DC converter load step response in Figure 9. The equivalent circuit diagram depicts the impedance network at each side of the converter. What distinguishes the simulations is that we are also capable of combining simulations of the physical powernet with simulations of SW models in co-simulations and, for instance, can model the impact of latencies in the SW logic and internal switching circuits. Combined with the comprehensive understanding of functional needs available at system providers like Bosch, this is a unique asset. Such information is valuable for designing the ECU-internal circuitry, dimensioning the safety, and for other response mechanisms. This can also be extended to distributed power supply solutions, e.g., by using models for communication latencies between distribution layers.

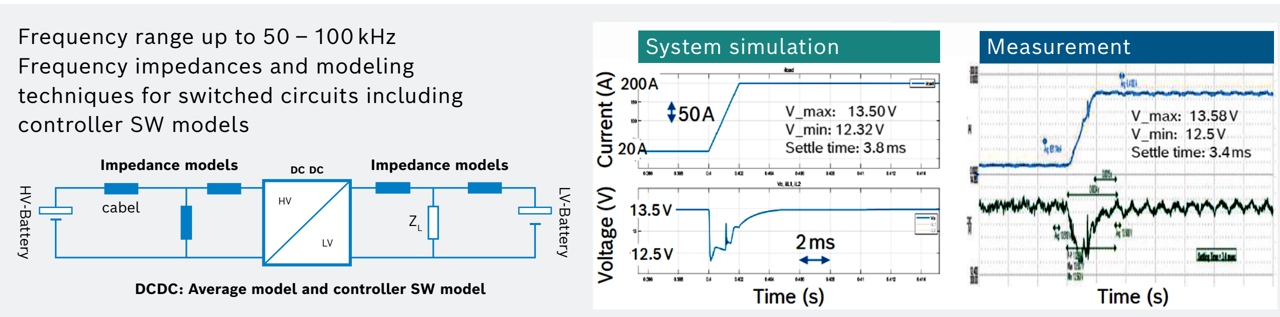


Figure 9: DC/DC converter: The correct system simulation (incl. software timings) of an example load step response is confirmed by later manual lab measurements.

08
Summary and Conclusions

New exciting functions in all vehicle domains bring the requirements on the powernet architecture to the next level. With the increasing demand for safe and reliable electrical supply, it is necessary to advance the designs of powernet architectures significantly. In this paper, we have presented an outlook on some of the major topics that will keep automotive manufacturers and suppliers engaged in the upcoming years.

New technologies such as eFuses and 48 V will significantly change powernets

Moving towards electronic power distribution solutions like Bosch's powernet guardian will enable manufacturers to bring more safety-critical loads to the vehicle for functions such as x-by-wire and automated driving. Zonal architectures will be pivotal for improved placement of powernet infrastructure and increase overall maintainability and reliability. With the newly released VDA recommendation 450, the design process and the implementation of safe powernet architectures will become more and more standardized.

The introduction of a 48 V supply level can reduce the weight of the wiring harness and improve the efficiency for high-performance loads in the low-voltage areas. However, such a move needs to be planned carefully and assessed in cooperations and studies between manufacturers and suppliers to realize a positive system TCO effect. As commonplace in E/E architecture, there is no one-size-fits-all solution – particularly with significant legacy constraints.

Powernet simulations help to master the new complexity

Simulation capabilities will be a major asset for powernet designers in the future. With sophisticated modeling capabilities of faults, transients, and external effects it is possible to assess the upcoming evolutionary and revolutionary steps in the powernet architecture economically and with fast feedback loops. This requires the extension of the modeling environment to additionally reflect the SW logic and communication paths in such complex systems.

Developing the future together

Overall, we are in a phase of massive transformation in the automotive industry. This also holds true for the powernet design. To build reliable, safe, and cost-efficient vehicles, it will require close collaboration between vehicle manufacturers and suppliers with full system competency like Bosch. We are positive that the future E/E architectures will provide the right infrastructure and great opportunities to build outstanding and attractive vehicles based on great engineering.

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