From 400 to 800 V – Effects on the High-voltage On-board Electrical System

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The first fully electric series vehicles equipped with 800-V technology will soon be launched on the market. The significantly increased voltage level compared to conventional 400-V systems results in numerous advantages. At the same time, however, the installed components also need to meet particularly high demands. Experts from Dräxlmaier describe the required design adaptations, particularly in the area of the on-board electrical system.

KEY CRITERIA FOR ELECTRIFICATION

In order to achieve a higher market penetration and acceptance on the user side, electric vehicles have to be able to convincingly deliver certain core competences: in addition to purchase price and range, this primarily concerns the charging time and the existence of charging infrastructures outside and within the city. Improving these key criteria presents automobile manufacturers with new challenges that can be mastered by continuously improving the performance of the high-voltage technology used. This process will eventually lead to higher ranges, shorter charging times,

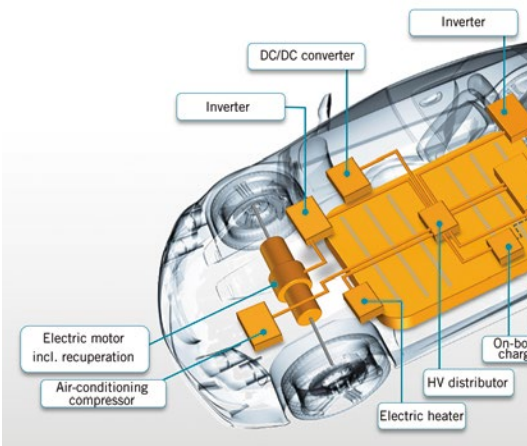

FIGURE 1 Standard components of a high-voltage on-board electrical system in an electric vehicle (© Dräxlmaier)

and higher driving performance. At the same time, care must be taken to keep the vehicle weight as low as possible.

These development goals also necessitate adjustments in the area of the high-voltage on-board electrical system, whose typical components are shown schematically in **FIGURE 1** on the basis of the LV 123 standard. In addition to the use of new or modified components that meet future requirements, special attention must be paid to the architecture of the on-board electrical system, its design, construction, testing and diagnosis in the context of product safety.

INTRODUCTION OF 800-V TECHNOLOGY

Many electric vehicles available nowadays are delivered with an on-board voltage of 400 V. However, an increase in the voltage level is generally regarded as an effective option for optimizing performance. With this in mind, 800-V systems have already been announced for serial use. Due to the doubled voltage, considerably more power can be transmitted in the same time at the same current strength, which leads to significantly shorter charging times. In purely mathematical terms, it is even possible to halve the charging time compared to a 400-V system. This can be seen from the equation for electrical energy "E" converted after time "t" in **FIGURE 2**. Nevertheless, thanks to a similar level of current as in the 400-V on-board electrical system, the cable cross-sections can be left almost unchanged, leading to practically no changes in the weight and potential heat losses. Both of these factors benefit the energy efficiency of the overall system.

CHALLENGES FOR FAST CHARGING

By using a powerful 800-V DC fast-charging infrastructure and vehicle components adapted to the increased voltage – including high-performance connectors and high-performance battery cells – the time required to reach an 80-% charge level can be reduced to less than 20 min for standard battery capacities. The charging time is always determined by the weakest link in the chain – which means that when a more powerful battery is used, the on-board electrical system must be designed in such a way that this does not become a bottleneck. **FIGURE 2** schematically shows the interaction of the charging infrastructure with vehicle components based on 800-V technology.

The highest continuous load on the high-voltage on-board electrical system does not occur during driving but during the charging process. **FIGURE 3** shows the current profile and temperature curve of a component – for example a plug-in system, a cable or a bus bar – in the main current path of an 800-V electric vehicle. The graph illustrates the effects of a test driving profile in the left half of the picture and an 800-V DC fast-charging process in the right half. The recording time of the driving profile is 0.5 h, the charging time is 20 min, which is slightly shorter.

Furthermore, it can be seen from the graph that high current peaks of up to 750 A are achieved when driving. Mathematically speaking, however, the dynamic load current curve results in a root mean square of only 230 A. The temperature increase (red line) in this operating state is almost logarithmic to about 95 °C.

During subsequent charging, the temperature of the component again rises significantly due to the permanent load. The gradual drop in the charging current is determined by the battery cells used and their thermal performance – the other on-board electrical system components align themselves accordingly. Charging starts at 500 A; after exceeding a temperature of about 140 °C, a reduction to 400 A is made. Over the course of time, the current strength continues to decrease gradually as certain temperature thresholds are reached. Due to the combination of permanent energy transmission and a high current load, the root mean square during charging reaches 350 A, which is significantly higher than during driving.

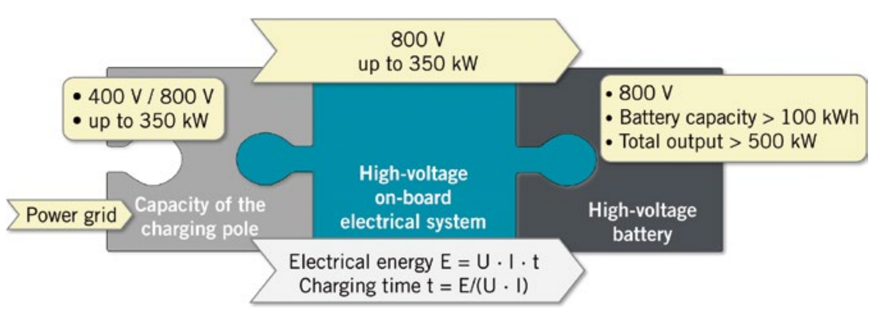

FIGURE 2 Requirements for the high-voltage on-board electrical system between the DC quick charging point and high-voltage battery (© Dräxlmaier)

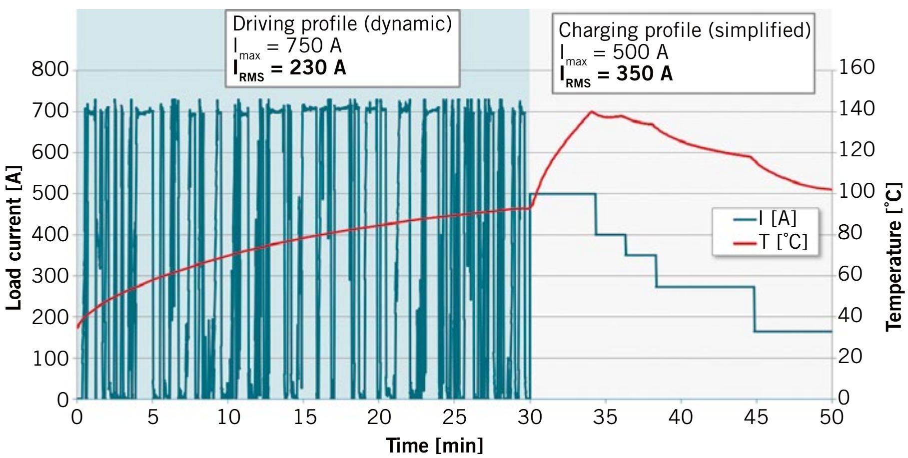

FIGURE 3 Current profile and temperature curve of a component in the main current path during driving (left) versus DC quick charging (right) (© Dräxlmaier)

These high energy and power requirements during the driving and charging situations place a heavy load on the components of the 800-V on-board electrical system and therefore require corresponding adaptations to the structural design of the overall system. In particular, the current peaks during driving operation can greatly reduce the service lifetime of smaller components with lower heat capacities or poor thermal conductivity. With rapid charging, on the other hand, the high effective value of the charging current must be taken into account for the thermal design.

ADVANTAGES OF THERMAL MANAGEMENT

Theoretically, the temperature of the on-board electrical system is proportional to the amperage squared. The same ohmic losses would be seen on the cabling with double the transmitted effective power and thus the same heating in the on-board electrical system. This applies under the premise of designing the on-board electrical system at a current level comparable to the conventional 400-V system and with identical cable cross-sections. This results from the following mathematical considerations:

$P_{N_{400\,V}} = U_{400\,V}\cdot I$ and

$P_{N_{800\,V}} = U_{800\,V}\cdot I$ result in

$$P_{N_{800\,V}} = P_{N_{400\,V}}\cdot\frac{U_{800\,V}}{U_{400\,V}} = 2\cdot P_{N_{400\,V}}$$

If an identical nominal power is assumed instead of a constant current strength, only a quarter of the temperature increase based on the ambient temperature can be expected when using an 800-V system compared to a 400-V system:

$$\Delta\vartheta = R_{Th}\cdot\dot{Q} = R_{Th}\cdot P_V = R_{Th}\cdot I^2\cdot R_{Ohm}$$

leads to

$$\Delta\vartheta_{800\,V} = \Delta\vartheta_{400\,V}\cdot\left(\frac{400\,V}{800\,V}\right)^2 = \frac{1}{4}\Delta\vartheta_{400\,V}$$

This contributes significantly to the efficiency of the 800-V technology compared with the currently used components with lower on-board voltage.

GEOMETRIC INTERPRETATIONS

Both 400- and 800-V systems are divided into the same voltage class B according to the LV 123 standard. However, the 800-V network is classified in the voltage level HV_3 compared to HV_2a at 400 V. This does not result in any design changes for the necessary air gaps.

When considering the necessary creepage distances according to IEC 60664-1, the situation is different: For example, a high-voltage plug with contamination level 2 and insulation material group 1 requires a doubling of the distance from 2 to 4 mm in direct comparison between 800- and 400-V technology. The insulation resistances also behave in the same way. For example, if standard LV 123 is applied to appropriately designed high-voltage cable sets, a doubling of 25 MΩ (500 V test voltage) to 50 MΩ (1000 V test voltage) must be planned.

MATERIALS FOR HIGH-VOLTAGE APPLICATIONS

The materials to be used in high-voltage components are defined by various general specifications, including standard LV 123. However, the specific design of each vehicle or vehicle category – such as hybrid or electric vehicles – must be adapted separately.

Components in 400- and 800-V on-board electrical systems must be designed equally for the temperature range from −40 to +140 °C. The thermomechanical properties and also the constant material properties such as dielectric strength or conductivity must be taken into account. The materials are also tested with regard to their geometric design as part of ageing tests and derating tests. Plastic components must also comply with other specifications in terms of their fire behavior.

Ultimately, the material selection for 400- and 800-V systems is almost identical due to the standardized test specifications for high-voltage components.

ELECTROMAGNETIC COMPATIBILITY

In the case of electromagnetic properties, however, there are differences between the two voltage levels. Electromagnetic interference and shielding currents are mainly caused by the conversion from DC to AC voltage in the inverter. At the moment of switching, the voltage drop across the inductance is equal to the on-board supply voltage. This leads to a doubling of the gradients of the current and voltage transients and thus also of the high-frequency interference compo-

Premises:
- Designed for the same amperage (in the 800-V system as in the 400-V system)
- Same cross-sectional areas of the cables

Interpretations	Basis of interpretation	Changes from 400 V to 800 V	Trend
Temperature	$\Delta\vartheta_{800\ V} = \Delta\vartheta_{400\ V} \cdot \left(\frac{400\ V}{800\ V}\right)^2 = \frac{1}{4}\Delta\vartheta_{400\ V}$	Same losses at double power, i.e., equal heating in the on-board electrical system (**unchanged**); with variable current, a quarter of the increase in warming occurs	↔
Geometric interpretations: Air gaps Creepage distances Insulation resistances	Requirement (LV123, HV_2a vs. HV_3) Calculation as per IEC 60664 LV 123: High-voltagecable harnesses	Minimum air gaps remain **unchanged** Generally, **doubling** the specifications for creepage distances and insulation resistances	↔ ↑↑
Materials: High-voltage components and high-voltage contact systems	LV 123, LV 126, LV 161, LV 214, LV 215, LV 216 …	Determined by specifications in the HV component design: 400 V = 800 V (**unchanged**)	↔
Electromagnetic compatibility (EMC)	$\frac{di}{dt} = \frac{U_L}{L} \Rightarrow \frac{di}{dt} = \frac{U_{BN}}{L} \Rightarrow \frac{di_{800V}}{dt} = 2 \cdot \frac{di_{400V}}{dt}$	**Doubling** of the gradients of the current transients and thus the high-frequency interference components	↑↑
Arc effect: Arc length Max. power output	Calculation based on [2] at 30 mΩ short-circuit loop impedance	Arc quenching during the separation process: **Doubling** of the arc length Power output from **max. 1.2** to **max. 5.0 MW**	↑↑

FIGURE 4 From 400 to 800 V: summary of the physical and normative changes (© Dräxlmaier)

nents and the shield peak currents in the 800-V on-board electrical system compared to the 400-V system.

In the low-frequency range, the transients are similar in both voltage levels; very high transients occur mainly in the radio frequency range with the 800-V on-board electrical system. These increased interferences must be taken into account in the high-voltage system design within the framework of DIN-EN-55025 conformity [1].

INCREASED ARC EFFECT

The most demanding design challenge resulting from the higher voltage level for the on-board electrical system concept is the increased stress on the components due to the arc effect. Although this is already apparent from 17 V, the quantities of energy – and thus its potential effects – increase with higher voltage. Reliable arc quenching must therefore be ensured, especially during switching and disconnection processes.

The calculated maximum arc length in air doubles from 210 to up to 420 mm when comparing on-board electrical systems with 400- and 800-V technology. Sand fillings in fuses or gel in pyro separation elements help to constructively reduce the arc length in practice.

While power outputs of up to 1.2 MW can already occur in 400-V networks during disconnection processes, the value in 800-V systems multiplies to up to 5 MW – in each case with a short-circuit loop impedance of 30 mΩ. For this reason, it is particularly important with 800-V on-board electrical systems to always protect the entire system [2]. To achieve this, fuses, plug connectors, and switch boxes must be designed and used according to new specifications.

FIGURE 4 summarizes the changes required when switching the voltage level from 400 to 800 V.

MAKING THE MOST OF THE BENEFITS OF HIGH VOLTAGE

In combination with the corresponding quick-charging points, the necessary waiting times for charging the vehicle battery up to 80 % can be significantly reduced by using an 800-V on-board electrical system. At the same time, the design of the required high-voltage components is sometimes very demanding compared to a 400-V on-board electrical system.

The required specifications generally double the creepage distances and insulation resistances, while the air gaps and the materials to be used remain almost unchanged. Furthermore, a suitable structural design must ensure that the increasing requirements with regard to complex thermal management are met. The doubling of the voltage level also doubles the electromagnetic field propagation in the high-voltage on-board electrical system, especially in the higher frequency ranges. The increased electric arc damage potential also places increased demands on the use of separating elements and fuses. At present, components such as contactors, relays or fuses from industry are often still used in the automotive sector.

Robust plugs or connector systems are required, especially for high-voltage on-board electrical systems with high current loads and impulses. By using flat connector systems with high voltage and current carrying capacity, such as the dHPT family developed by Dräxlmaier, Class 5 high-voltage fast-charge connector systems can be realized for applications using direct currents up to 1000 V and 500 A.

WHAT DOES THE FUTURE HOLD?

In line with the rapidly growing electric mobility market, the use of high-voltage on-board electrical systems will also increase sharply. In addition, constantly increasing battery performances and reduced charging times are to be expected, so that the performance of the on-board electrical system will continue to play a decisive role. A strong focus will be on thermal management and the electromagnetic compatibility of all components.

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