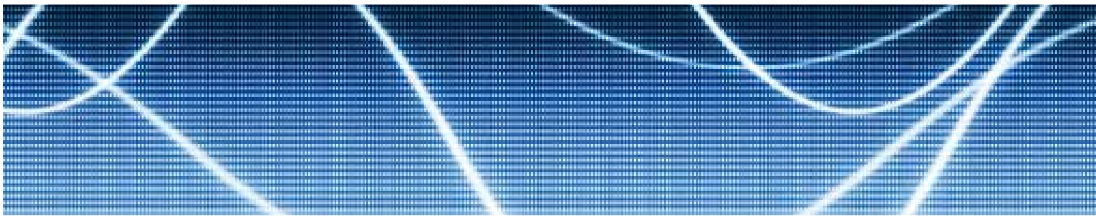
ZVEI:
Die Elektroindustrie

Voltage Classes for Electric Mobility



German Electrical and Electronic Manufacturers' Association

Voltage Casses for Electric Mobility

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1 Target Group and Objectives

Electric mobility is a dynamic field of development. New technologies stand alongside traditionally reliable approaches to electrical engineering and electronics and the systems which connect them to standard internal combustion engine technology.

This document provides an overview of the current state of technology and standardisation of the relevant voltage classes. It is intended for professionals and interested stakeholders in development, technology, production and repair service dealing with powertrain electrification. ZVEI working groups and members involved in component-specific activities in some vehicle areas are also given the opportunity to expand their knowledge from an overall system perspective.

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2 Editorial

A look into the history of the automobile shows that many of the first non-horse-drawn carriages were fitted with an electric drive. The fact that history was shaped by internal combustion engines in the following decades can be attributed to the extensive development efforts that helped overcome the engine's initial susceptibility to breakdowns and awkward handling, making it a practical solution for long distances. Following intensive research and development in the field of electric mobility, we now know that this innovative technology not only addresses environmental concerns, it also significantly increases driving dynamics and driving pleasure. This suggests that powertrain electrification will continue to increase and attract the interest of a growing number of buyers.

Renewed interest in e-mobility or hybrid technology – and hence electric drives – has its origins in eco-political objectives. The introduction of all-wheel drive hybrid vehicles demonstrated that significant speed values and hence impressive acceleration values can be achieved with two different drive technologies (thermal motor plus electric machine) working in parallel. This provided the impetus that was needed to develop e-mobility to its current stage. Any marketing expert knows that if you make driving more fun, you will attract more buyers; a sales argument which tips the balance even in the face of possible additional costs.

The 2015 CO2 emission targets set by the European Commission under the Kyoto Protocol are virtually impossible to meet with traditional internal combustion engine technology. Moreover, non-compliance will result in fines if the average CO2 emissions of a manufacturer's fleet exceed its limit values. Hybrid technology can help address this risk since it enables CO2 emissions to be reduced by 10–20 percent on average based on the New European Driving Cycle. The European Commission also envisages a target of 'zero emissions' for European city and town centres in the future. This requires the use of vehicles that can be driven exclusively by electrical power, at least for shorter distances.
So much for the renaissance of the electric vehicle!

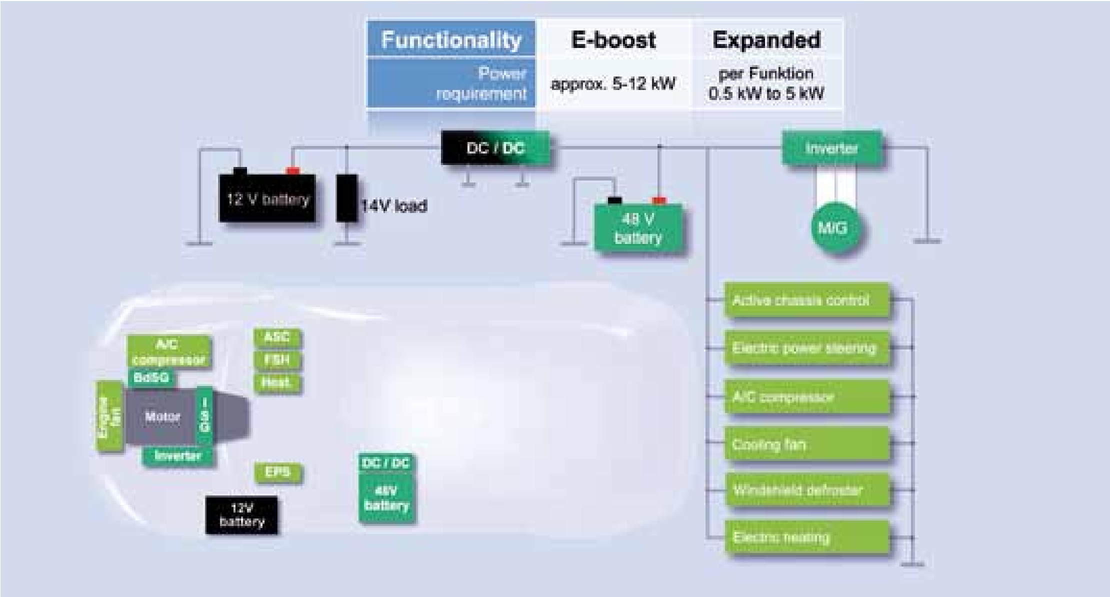
Until recently, the majority of hybrid drives came from Asia. Market-driven competition paved the way for this technology to be adopted in vehicles inside and outside Europe. This resulted in an engineering boom that coincided with the availability of high-voltage components already used for military and aerospace applications, by industry and for traction systems (tramways and trains, etc.). But these components far exceeded automotive requirements and did not match the prices envisaged by the carmakers. Although these components were initially installed in early non-Asian hybrid vehicles, they have been gradually replaced by more suitable components that had first to be specified, developed and manufactured.

Today, a wide variety of high-voltage components is available that meet the technical requirements at prices that seem to be acceptable to the automotive industry. Hybrid drives are thus likely to become more attractive in terms of pricing in addition to their dynamic driving benefits.

In view of the evolving hybrid mechanisation of passenger and commercial vehicles it can be assumed that the architectures illustrated below with the options currently available (see fig. 1–3) will be used in the majority of vehicles in the near future.

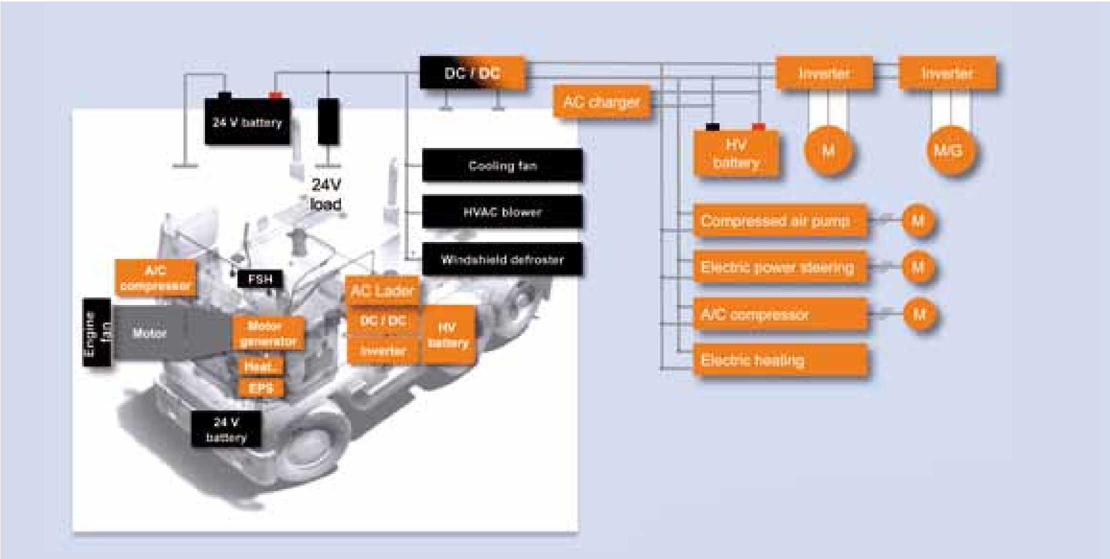
- Traditional 12/24 volt level for all current vehicle and convenience features
- 48 volt level for one to five kW consumer installations and application in mild hybrids for boost and energy recuperation functions up to max. 12 kW (green)
- High-voltage level for hybrid and electric vehicles for boost function, energy recuperation and electric driving greater than 12 kW (red/orange)

Fig. 1: **14 V – 48 V basic architecture**



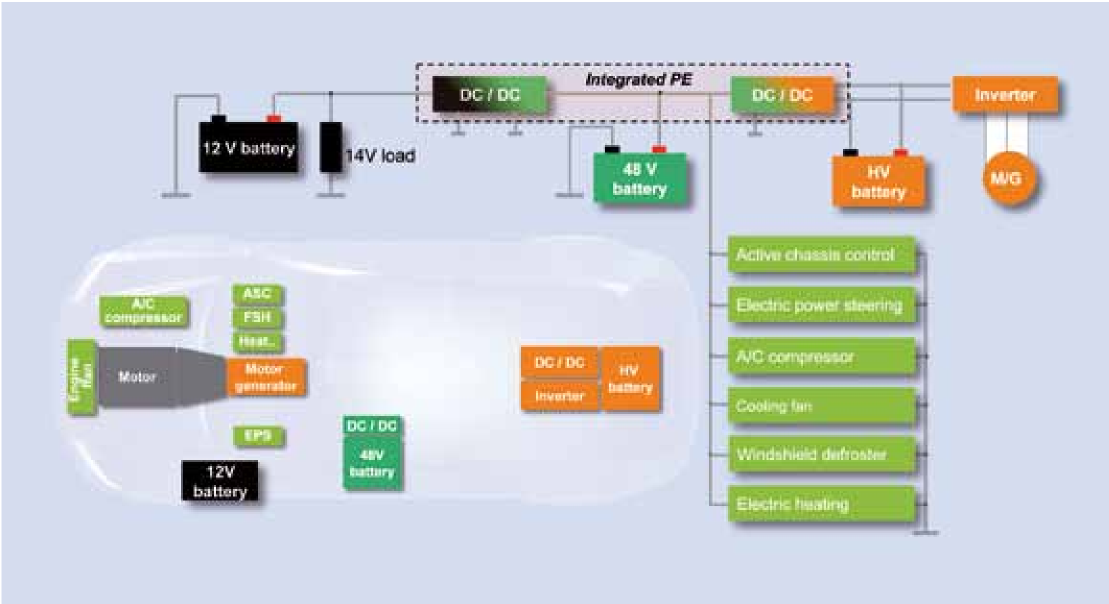
Source: Delphi Deutschland

Fig. 2: **24 V – HV – E/E system, commercial hybrid vehicle**



Source: Delphi Deutschland

Fig. 3: 14 V – 48 V – HV – E/E system, hybrid vehicle



Source: Delphi Deutschland

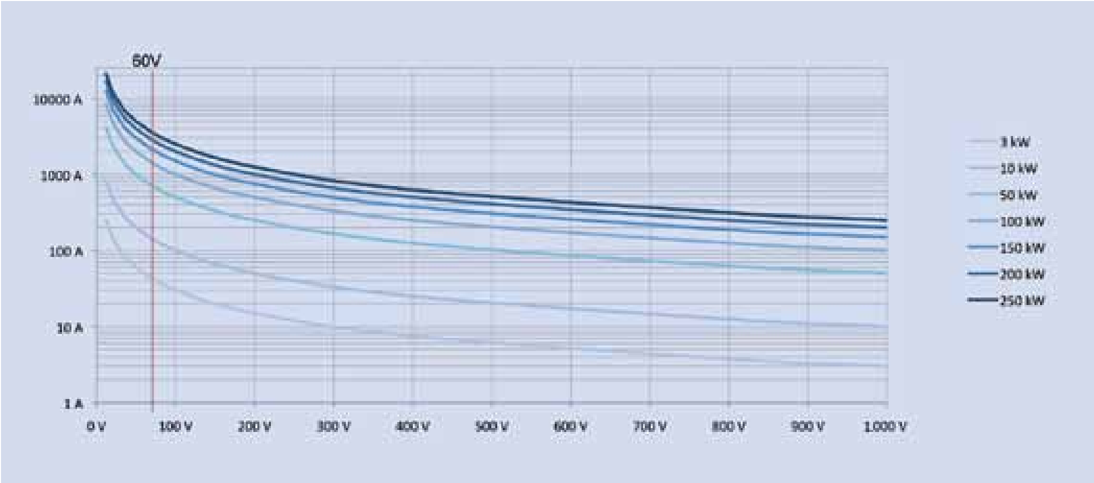
The following pages focus on the current status of the different voltage levels and their use in passenger and commercial vehicles. The technical impact of the components used in hybrid vehicles is also analysed in detail in this document, although voltage levels within the e-mobility infrastructure are not covered.

3 Technical Introduction

In view of the dedicated efforts of the automotive industry to implement powertrain electrification, the question arises as to whether the necessary applications are technically feasible, given the voltage levels that will be needed.

Whilst voltages in excess of 12/24 V have previously been reserved for industrial and household applications, the voltages required for the electric drive power in passenger and commercial vehicles are several hundred volts higher.

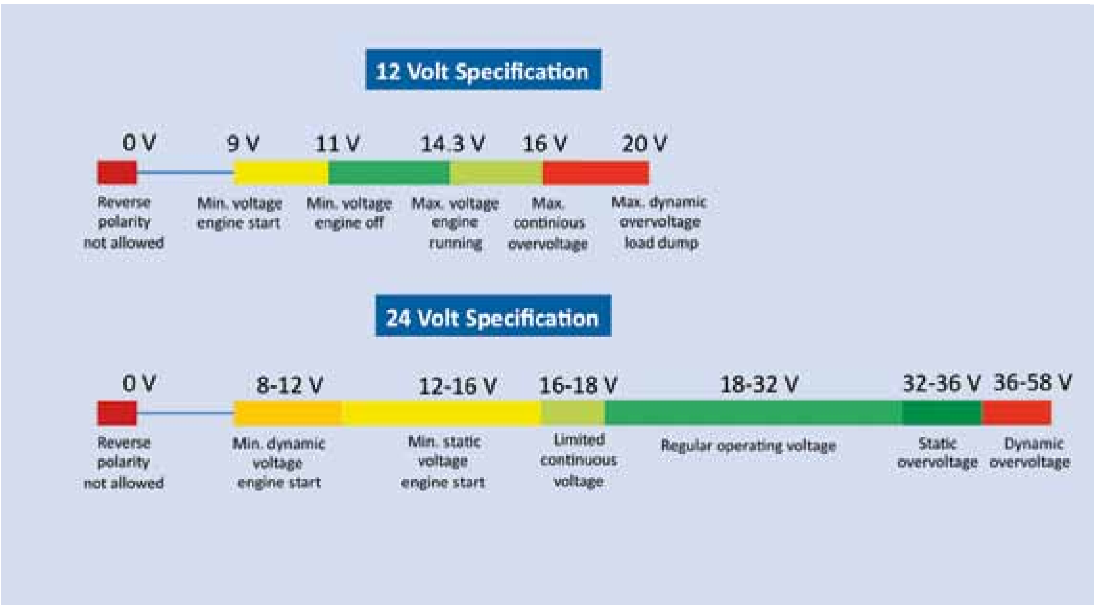
Fig. 4: **Engine and battery current – system voltage**



Source: Lenze Schmidhauser

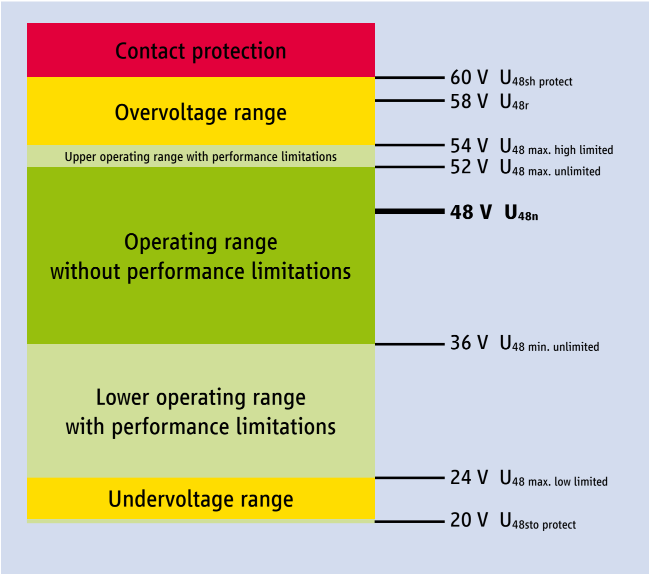
Moreover, functions that are currently mechanically powered in thermal drive systems must be electrically operated in the future, decoupled from rotational speed and torque and hence from the state and behaviour of the internal combustion engine (if present). While the VDE has standardised almost all established voltage levels, there is currently no valid standard available for voltage ranges greater than 60 V DC in vehicles.

Fig. 5: **Voltages in the 12/24 volt on-board system**



Source: ZVEI

Fig. 6: Voltages in the 48 on-board system



Source: Delphi Deutschland

State of the art

Common voltage levels of 12/24 volt are still used for supplying most of the vehicle and convenience features and will continue to do so in the future.

The choice of voltage levels for the different electric and hybrid drives is determined by the relevant application within the electrical powertrain, resulting in great variation and individuality.

The electrical architectures and their physical implementation are also adapted to the relevant requirements of the powertrain. Standardising them would make a genuine difference in terms of costs.

Higher voltages – and hence lower currents – provide cost benefits primarily in terms of energy distribution (connectors, cable cross-sectional areas, etc.). Lower voltages are preferably used for battery technology due to lower costs since the number of cell connections can be reduced, making battery management less complex.

A holistic approach must be taken to the selection of (cost) optimal voltage since it cannot be satisfactorily resolved from the perspective of components alone.

While electrical drive components in industrial applications are designed with expensive spare capacity/redundancy reserves in terms of their installation space and continuous load, this is not an option for the cost-aware and high-volume car manufacturing industry. The electrical architectures and their physical implementation are currently adapted to suit individual vehicle requirements. Standardisation will help to optimise costs, but it will take some time before the automotive industry agrees on standard structures and components based on practical experience.

It is clear that high voltages are required to transport power in the 100 kW range that keep the current values within reasonable limits during the actual transfer process.

Electrical power transmissions of this size for stationary or mobile applications such as trains or forklifts have been operated and maintained by trained electro-technical personnel to date. However, lay persons gain access to this technology when it is transferred to passenger cars. Therefore it is necessary to ensure they are protected from accidental contact with dangerous voltages. This applies to normal vehicle operation and maintenance. Even in the event of an accident, safety must be ensured. This subject will be discussed in detail later.

4 New 48 V Low-Voltage Level

It is already evident today that a third voltage level of 48 V will become established in addition to the 12/24 V and high-voltage levels. This new level is intended to supply electrical components of more than 3 kW power, such as the start-stop feature (boost and energy recuperation), air conditioning compressors, electrical heaters, pumps, steering drives and no doubt several other features (audio, etc.) in the future.

In terms of technology, the 48 V voltage level reflects the key points developed for the 42 V standardisation at the turn of the millennium. This is to be welcomed from today's perspective since the findings at the time can be largely adopted while staying below the VDE low voltage limit (lower than 30 V AC, lower than 60 V DC), which seems to render obsolete extensive personal safety measures such as contact protection, equipotential equalisation and insulation control. However, monitoring contacts are envisaged for connectors to prevent what is known as 'hot plugging'.

Fig. 7: Electrical heater

Source: Webasto Thermo & Comfort

5 High Voltage

Electrical powertrain performances of more than 12 kW are now reserved for the high-voltage range, whereby the voltage level required is based on the currents to be transmitted of approx. 250 A.

While battery voltages of up to 400 V are envisaged for passenger car hybrid technology, voltages of up to 850 V are planned for commercial vehicles. These voltages lie within the voltage class B. The high-voltage level is max. 60 < U ≤ 1500 V DC, 30 < U ≤ 1000 V AC rms.

Table 1a: Vehicle types and power categories considered

E-mobility performance class overview for passenger vehicles										
		Mild Hybrid			Full Hybrid/Plug-in		EV (Batt/RE/FC)			Unit
		12 V	48 V	HV	mid	Power	Small car	Medium car	Sports car	
max. EM Power	motor-based	4	12	20	60	100	60	100	180	kW
max. EM Speed	motor-based	50	150	150	200	300	200	300	500	Nm
DC voltage	max. (generator-based))	15	60	200	400	450	400	400	450/800	V
	min. (motor-based)	12	36	120	300	250	300	300	300/600	V
max. current	DC	333	333	167	200	400	200	333	550/280	A
	AC	350	500	500	600	800	250	450	1000/500	A
Speed/crankshaft speed ratio or max. EM speed		3	1	1	1	1	10 – 15 k/min		bis 20 k/min	
Power ratio max./duration		2	2	2	2	2.5	1.5	1.5	2	

Source: ZVEI

Table 1b: Vehicle types and power categories considered

E-mobility performance class overview for commercial vehicles/buses										
		Mild Hybrid (up to approx. 40% internal combustion engine power)				**Plug-in Hybrid**	**EV/RE/FC**			**Unit**
		< 7.5 t	7.5 – 12 t	> 12 t	Bus (18 t)	7.5 – 12 t	< 7.5 t	7.5 – 12 t	Bus (18 t)	
max. EM Power	**motor-based**	50	65	120	120	90	100	120	2x 120	**kW**
max. EM Speed	**motor-based**	350	450	1000	1000	500	350	450	2x 500	**Nm**
DC voltage	**max. (generator-based))** **min. (motor-based)**	400 280	420 300	420/800 300/600	420/800 300/600	420 300	420 300	420 300	800 600	**V** **V**
max. current	**DC** **AC**	180 300	220 350	400/200 450/250	400/200 450/250	300 450	330 450	400 450	400 2x 250	**A** **A**
Speed/crankshaft speed ratio or max. EM speed		1	1	1	1 – 1.6	1	10 k/min	10 k/min	10 k/min	
Power ratio max./duration		1.5	1.5	2	2	1.8	2	2	2	
Remarks		Apparently no longer pursued						Apparently no longer pursued	Axis with 2 EM	

Source: ZVEI

5.1 Definition of 'High Voltage'

In the automotive industry, high-voltage refers to voltages above 60 V. The classification of voltages in extra-low, low, medium, high and extra-high voltage has its origins in plant and building services engineering, which is particularly evident in the detailed description of earthing and isolation conditions. Whilst this differentiation is helpful for industrial applications, when specifying vehicle voltage classes it is more useful to distinguish between low and high voltage. In this way, lay persons can easily recognise the increased risk associated with higher voltage. This is why the rated voltage of all energy distribution components is colour-coded orange specifying live components.

6 Connection to Charging Infrastructure

Low voltage standards also apply to the entire charging infrastructure of e-vehicles and – in line with an agreement between IEC and ISO of 2011 – during the charging process to all electric circuits in a vehicle that are galvanically connected to the charging infrastructure [9]. This kind of electrical isolation is only available in vehicles fitted with on-board chargers with galvanic isolation or in the case of inductive charging systems. No galvanic isolation is required for vehicles using DC charging. Consequently electrical isolation must be ensured by grid-side charging stations.

This would therefore suggest that a vehicle's HV system is always galvanically isolated from the power supply system. This is generally referred to as IT (isolated terra) system. The vehicle chassis is earthed during charging via the infrastructure in line with IEC protection class 1.

Only if both poles of an electric voltage source/poles are touched simultaneously, does this result in an electric shock. In contrast to installation and building technology, isolation monitors can be used in vehicles to identify and eliminate potential risks when the first fault occurs before a second fault enables both poles to be touched.

Table 2: Voltage levels

Voltage levels in the automotive sector							
Protection class	Name	Upper limit AC V_{eff}	Upper limit DC V	Applicable standard	Other common names	Contact protection	Remarks
III	Functional Extra Low Voltage	25	60	No research result	FELV		No special protection to ensure safe isolation from other electric circuits with higher voltages
III	PELV – Protective Extra Low voltage	25	60	IEC 50178	PELV	without	If equipotential bonding is required between the electric circuits to prevent sparking e.g. in boiler plants with explosive gases as well as for HiFi systems
III	Saftey Extra Low voltage	25	60	IEC 61140	SELV	without	Compared to extra-low voltage, special protection required against electric circuits with higher voltages, e.g. safety transformers
III	Extra-Low voltage	25	60	IEC 60449	ELV	without	
III	Extra-Low voltage	50	120	IEC 60449	ELV	with	
II	Low voltage	1000	1500	EN 50110		double	In the automotive industry, the term 'high voltage' has become established for this voltage class. It emphasizes the fact that unlike e.g. the 12/24 V class, this protection class is dangerous for people if no additional protective measures are provided.
I	Medium voltage	approx. 36000		country-specific		clearance required	Specially trained staff, regulations with national focus
0, I	High voltage	> 36000		country-specific		clearance required	Specially trained staff, regulations with national focus

Source: ZVEI

7 Interactions between Different Voltage Levels

The different voltage levels used in vehicles must be able to operate separately from one another, independently and simultaneously. Standard fusing procedures must be used for the individual voltage levels to ensure cable and short-circuit protection. This can be achieved with safety fuses or electronic protection processes. In the event of faults occurring between two different voltage levels, careful consideration must be given to the design of protective circuits and detection systems and additional measures put in place if required. Whilst it is advisable to galvanically separate different LV voltage levels, galvanic isolation is imperative between HV and LV system(s). Maximum protection can be provided by spatial separation of the circuits to ensure as few physical contact points as possible, which eliminates the risk of a short circuit almost entirely.

It is recommended that HV cables and connectors be colour-coded orange to provide a visual warning.

Table 3: Voltage levels in passenger vehicles

Voltage levels in passenger vehicles								
Components	Mild Hybrid			Full Hybrid/Plug-in		EV (Batt/RE/FC)		
	12 V	48 V	HV	mid	Power	Small car	Medium car	Sports car
Drive and charging components								
Electric motor (rated voltage)	12	36	120	300	250	300	300	300/600
Inverter DC/AC	15	60	200	400	420	400	400	420/800
Voltage converter DC/DC	--	60–12	200–12	400–12	450–12	400–12	400–12	800/420–12
Charger AC/DC	--	--	--	--	230/420	230/400	230/400	230/450/800
Battery	15	60	200	400	420	400	400	420/800
Sub-component power								
Compressor	12	36	120	300	250	300	300	300/600
Heater	36	36	36/120	36/300	36/250	36/300	36/300	36/300
Electric pumps	12	36	12	12	12	12	12	12
Steering	12	36	12	12	12	12	12	12
Energy transfer components								
(Trad. on-board system)	12	12	12	12	12	12	12	12
Power distributor	12	60	200	400	420	400	400	420/800
Cable	12	60	200	400	420	400	400	420/800
Connector	12	60	200	400	420	400	400	420/800
Isolating elements	12	60	200	400	420	400	400	420/800
Relays/contactors	12	60	200	400	420	400	400	420/800

→ Continuation

Components	Mild Hybrid			Full Hybrid/Plug-in		EV (Batt/RE/FC)		
	12 V	48 V	HV	mid	Power	Small car	Medium car	Sports car
Integrated components								
Power semiconductor	75	75	250	650	650	650	650	650/1.200
Capacitors	16.5	66	220	440	462	440	440	460/880
Resistors	16.5	66	220	440	462	440	440	460/880
Inductors	16.5	66	220	440	462	440	440	460/880
Relays/contactors	16.5	66	220	440	462	440	440	460/880
Fuses	16.5	66	220	440	462	440	440	460/880
Current sensors	12	12	12	12	12	12	12	12
Position sensors	12	12	12	12	12	12	12	12
Temperature sensors	12	12	12	12	12	12	12	12

Source: ZVEI

Table 4: Voltage levels in commercial vehicles

E-mobility voltage level overview for commercial vehicles. buses								
Components	**Mild Hybrid** (up to approx. 40% internal combustion engine power)				**Plug-in Hybrid**	**EV/RE/FC**		
	< 7.5 t	7.5 – 12 t	> 12 t	Bus (18 t)	7.5 – 12 t	< 7.5 t	7.5 – 12 t	Bus (18 t)
Drive and charging components								
Electric motor (rated voltage)	280	300	300/600	300/600	300	300	400	600
Inverter (DC/AC-Wandler)	420	420	420/800	420/800	420	420	420	800
Voltage converter DC/DC	400 - 12	400 - 24	420/800 - 24	420/800 - 24	420 - 24	420 - 12	800 - 24	800 - 24
Charger AC/DC	--	--	--	--	3x400/420	3x400/420	400/420	3x400/800
Battery	420	420	420/800	420/800	420	420	420	400/800
Sub-component power								
Compressor	420	420	420/800	420/800	420	420	420	800
Heater	12/48	24	24	800 - 24	24	12	24	800 - 24
Electric pumps	12/48	24	420/800 - 24	24	24	12	24	24
Steering (electro-hydraulic)	hydraulic	hydraulic	hydraulic	hydraulic	hydraulic	(420 - 12)	(420 - 12)	(800 - 24)

Source: ZVEI

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→ Continuation

Components	Mild Hybrid (up to approx. 40% internal combustion engine power)				Plug-in Hybrid	EV/RE/FC		
	< 7.5 t	7.5–12 t	> 12 t	Bus (18 t)	7.5–12 t	< 7.5 t	7.5–12 t	Bus (18 t)
Energy transfer components								
(Trad. on-board system)	12	24	24	24	24	12	24	24
Power distributor	420	420	420/800	420/800	420	420	420	800
Cable	420	420	420/800	420/800	420	420	420	800
Connector	420	420	420/800	420/800	420	420	420	800
Isolating elements	420	420	420/800	420/800	420	420	420	800
Relays/contactors	420	420	420/800	420/800	420	420	420	800
Integrated components								
Power semiconductor	650	650	650/1200	650/1200	650	650	650	1200
Capacitors	450	450	450/880	450/880	450	450	450	880
Resistors	450	450	450/880	450/880	450	450	450	880
Inductors/motor coils	450	450	450/880	450/880	450	450	450	880
Relays/contactors	450	450	450/880	450/880	450	450	450	880
Fuses	450	450	450/880	450/880	450	450	450	880
Current sensors	12	24	24	24	24	12	24	24
Position sensors	12	24	24	24	24	12	24	24
Temperature sensors	12	24	24	24	24	12	24	24

Source: ZVEI

8 Batteries

A short overview of battery technology is provided at this point, For more detailed information, please refer to the book by Dr. Reiner Korthauer on lithium-ion batteries ('Handbuch Lithium-Ionen-Batterien') published by Springer.

Lead-acid accumulators have been used to store electrical energy in conventional vehicles for many decades. They have a nominal voltage of 12 V to 14 V (passenger cars) or 24 V (commercial vehicles).

The most common type of battery used for electric and hybrid vehicles are lithium-ion batteries (Li-ion, LiB). The main driver for the use of Li-ion batteries is their considerably higher energy density (Wh/kg) compared to lead-acid storage cells, which is essential for delivering adequate ranges in everyday electric driving. However, the price of these storage media is also significantly higher. This is due to the costs of manufacturing the battery cells and the need for electronic and thermal management to make them suitable for use in automotive applications.

The energy volume (battery capacity) required by vehicles is largely determined by the target electric driving range, the vehicle weight and dynamic behaviour (acceleration capability, braking with or without regeneration). A distinction is made between all-electric cars (BEVs) and hybrid-driven vehicles (HEVs). Although the battery capacity in most all-electric cars ranges between 16 kWh and 25 kWh, it can sometimes be significantly higher.

The electric range of hybrid vehicles is usually very limited, which is why batteries with significantly lower capacity, mostly in the single-digit kWh range, are used.

Batteries can also be differentiated in terms of cell optimisation. The cells of all-electric BEVs are mainly energy-optimised whereas HEVs use performance-optimised cells.

Key criteria for battery design:

- Gravimetric energy (Wh/kg)
- Volumetric energy (Wh/l)
- Peak performance (W/kg)
- Cold start performance (W/kg)
- Price (euro/kWh)

The specifications for battery life, quality and safety are also essential requirements that must be met.

Architecture and Functionality

Battery cells are mechanically arranged in a block consisting of several individual cells. Several of these blocks then form a battery. The total battery voltage is the voltage of an individual cells multiplied by the number of cells in series.

The cell voltage is determined by the cathode and anode materials used. The choice of electrode material depends on the requirements concerning temperature stability, electric capacity, charge and discharge currents and the number of charge and discharge cycles. The choice of electrolyte and separator is also very important.

Cells come in different formats, typically: cylindrical, prismatic or pouch.

The cell voltages of Li-ion batteries range from 3 V to 4 V, which means that a great number of cells must be connected in series for a total battery voltage of e.g. 300 V. In electrical terms, a battery consists of the battery cells, the block monitoring, the so-called battery management system and safety disconnect elements that must ensure the disconnection of the vehicle's battery terminals. A mechanical disconnection option must also be provided for HV batteries to enable service or maintenance work or in the event of an accident.

The block monitoring balances the cells' level of energy ensuring maximum charging or discharging of the cells. When assembled in a series configuration, the weakest cell determines when the charging or discharging process is stopped. The charging process stops when the weakest cell is full or, in the event of discharging, empty, even if the other cells still had some reserves. This is where cell balancing comes in to enable best possible charging and discharging of the other cells. There are two main options for this: active and passive balancing. Active cell balancing actively moves energy from one cell to the other, while passive balancing converts excess energy into heat.

The battery management system (BMS) controls the charging and discharging process of battery cells, i.e. it determines when and how much current can be provided by the battery and hence used.

Li-ion batteries have a limited temperature range compared to the vehicle operating temperature range. Low temperatures impair the charging and discharging of energy. High temperatures accelerate cell ageing. The BMS must therefore provide sufficiently cooling and heating to ensure that battery temperatures stay within the suitable temperature range.

The BMS controls communication between the battery sub-modules and other control units such as the charging station, the DC/DC converter and, of course, the inverter. It also determines the battery key performance data (state of charge, depth of discharge, state of health) that are also provided to other electronic control units.

9 Charging Voltages

9.1 AC Charging Voltages

EU standard:	230 V AC single-phase	➔	3.3 kW peak charging capacity
	400 V AC three phase	➔	22 kW peak charging capacity
Outside the EU:	110 V AC single-phase	➔	3.3 kW peak charging capacity

9.2 Charging Voltage for DC Fast Charging

The battery voltage must be connected and adjusted to the relevant grid voltages to enable charging of electric vehicles. This task is performed by battery chargers built into modern electric vehicles.

Direct current fast charging is used today to speed up the charging process of electric vehicles. The charging station is directly connected to the vehicle battery. No on-board charger is required for this charging method. However, the charging stations must be able to adapt to the battery's voltage level and the key performance data required for charging (charging state, charging voltage, max. charging current) must be exchanged between the vehicle (battery) and charging station. The vehicle controls the charging process during this communication exchange, while the charging station controls current and voltage supply.

The 'CHAdeMO' interface is the incumbent standard originally developed by TEPCO in Japan. Technical data: 500 V, 125 A. In theory, it takes approx. 20 minutes to almost fully charge a 20 kWh battery. Some 1000 stations have now been installed in Japan. Several Asian vehicles are already equipped with this interface.

European car manufacturers have adopted the 'combo type 2' charging interface that supports the combined charging system developed specifically for this purpose. This interface enables both AC and DC charging. The majority of European OEMs have agreed to use this interface for all electric vehicles from 2017.

It is designed for voltages up to 850 V and currents up to 200 A.

Table 5: Drive unit concepts

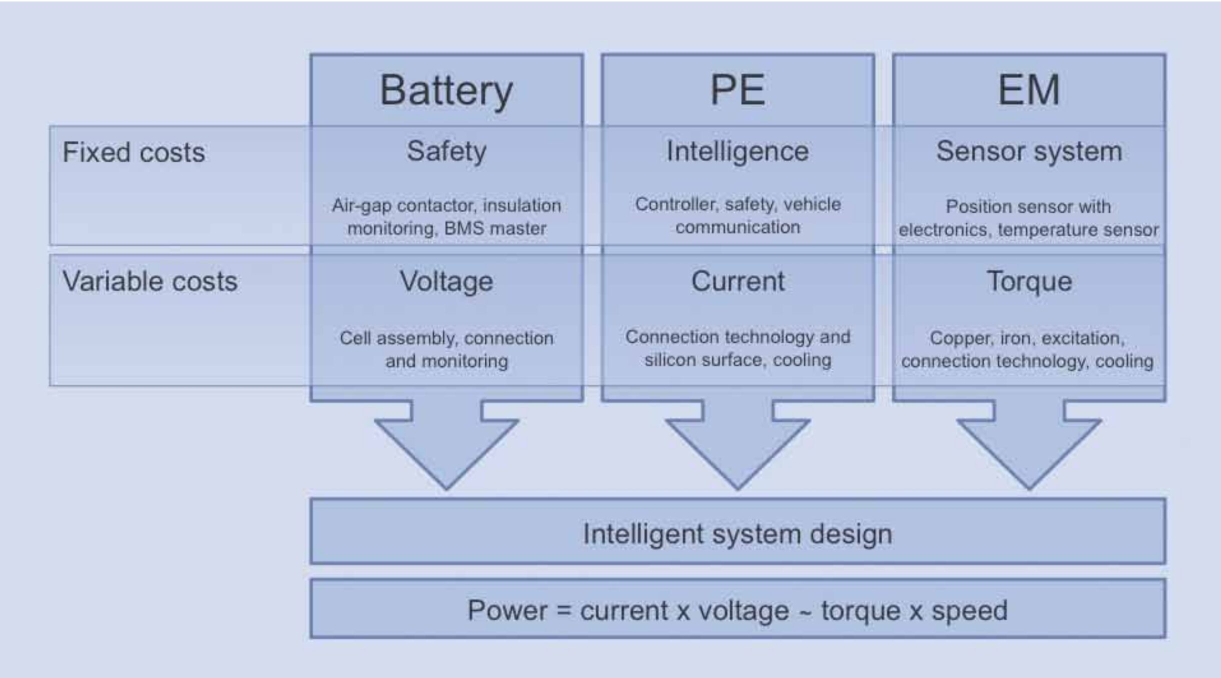
Type of electrification		Parallel hybrid	Power-split HEV Sp2	Sp3
Characteristic	48 V	300 V AC 450 V DC	600 V AC 900 V DC	1000 V AC 1500 V DC
Power (approx.)	up to 20 kW	up to 50 kW	150 kW	
Cooling fan	Air	Water	Water	Water
Enclosure design	open	closed	closed	closed
Cover design	Plastic and new materials permitted		Sheet steel, die-cast aluminium, etc. (crash safety)	
COD, Pilot Line	not required	required	required	required
Contact protection	none	required	required	required
Terminal connections	open (crash protection)	closed	closed	closed
Corrosion protection	Required for DC (e.g. for integrated PE on EM)		e.g. IP6K7	
Winding technology	Automotive industry standards can be used		Additional measure regarding insulation resistance (thickness, interphase isolation, clearances …)	
Number of turns (winding)		'increase' with voltage		
Interphase insolation	non required	recommended	mandatory	mandatory
Test voltage	500 V	2x U_{nenn} + 1000 V	2x U_{nen}n + 1000 V	2x U_{nenn} + 1000 V
EMC	critical with increasing voltage			
Sheet stack	Iron core (laminations) largely synergetic between the different voltage levels			

Source: ZVEI

10 Impact on Component Costs

The complete system consisting of energy storage system, e-machine and power electronics must be considered as a whole to ensure optimal pricing. Cost drivers may vary depending on the component.

Fig. 8: Component Costs



Source: ZF Friedrichshafen

10.1 Improved Performance with Higher Voltages

The electrical performance can be increased by using higher current or voltage rates. The use of higher current rates to improve performance is determined by the system design, because higher current flows require the internal and external pin contacts (power modules and connectors) and cabling to have greater cross-sectional areas.

Since the current level cannot be increased above 250 A due to physical limitations, improved performance in passenger/commercial vehicles can be achieved with higher voltage rates.

A detailed description of the individual components is provided in the following chapters.

11 Power Electronics

Power inverters and DC/DC converters use semiconductors as periodically operating switches to minimise losses when changing the output voltage. In this way, DC and AC voltage states can be produced and the torque and speed of electric machines or the DC output voltage of a converter controlled.

The switching process itself and the current to be switched generate thermal losses that must be dissipated via cooling surfaces. The higher the ambient temperature and electrical current, the larger the surfaces required for the chips. However, the semiconductors and circuit concepts deployed differ in terms of their current-related on-state power and switching losses. The use of high-frequency switching can reduce passive inductive components especially in power converters. High-speed electric machines also benefit from increased switching frequencies since motor losses and noise emissions can be reduced.

The currently available semiconductors such as IGBTs and MOSFETs or SiC diodes have been developed and optimised for stationary and on-grid applications. IGBTs generally used for 200 V applications and above have a blocking voltage of 600 V and 1200 V, which makes them suitable for use in all global power transmission systems. The transmission systems can be divided into two main voltage classes: single-phase 220 V – 240 V level and three-phase 380 V – 440 V level. The resulting voltage amplitudes can lead to said IGBT blocking voltages. Due to technical limitations, voltage reserves prevent full utilisation of these semiconductors up to the blocking voltage limit. It would appear that they are suitable for maximum DC voltages of 420 V and 800 V (see table 3, page 14 and table 4, page 15).

The higher the DC voltage selected, the lower the current flow required for the same power output, thus enabling maximum power transfer at peak voltage. Reducing the DC voltage proportionally reduces the transmittable power and increases the costs per kW.

Power electronic components use capacitors to buffer the reactive power. Designed as electrolytic or film capacitors, they are available in finely graduated increments for different DC voltages and can therefore be optimised and procured even in modest quantities.

The same applies to printed circuit boards and the internal circuiting of an inverter's power components: higher voltages reduce costs because the necessary currents can be reduced. Special attention must be paid to the maximum currents occurring in printed circuit board, especially in the semiconductors themselves, because their fine structures reach the maximum permissible temperatures after only a short time (0.1-10 s). Unlike motors, connectors and cables, power semiconductors must be designed for permanent load at the required maximum currents to achieve substantial cost savings by reducing maximum current.

To minimise total losses and EMC interferences, inverters and DC/DC converters must be designed with intelligent circuitry concepts.

12 Contactors

High-voltage waveform and current rates have a substantial impact on the costs associated with electromechanical components, such as connectors and contactors.

The technical requirement for contactors is that it must be possible to switch live components if necessary (galvanic isolation). Key characteristics are the current carrying capability, maximum voltage and making/breaking capacity under the maximum possible load conditions.

Precharge relays that charge the DC-link capacitors of the power electronics via a resistor are often used to reduce current peaks during the activation process. Only then are the main contactors sequentially switched within a set time interval.

Contactors also provide short-circuit protection within chemical energy storage systems and must therefore ensure that direct currents are reliably switched off in the event of a short circuit. The breaking capacities of load contactors occurring in this case are determined by the current-voltage product in the event of load breaking and may have several 100 kW. Therefore the operating conditions for the switching elements of contactors must ensure maximum arc suppression. This can be achieved with a vacuum or with special gas fillings and additionally with magnetic blowouts near the switching contacts, which physically move the arc away from the contacts. These technical measures significantly increase costs.

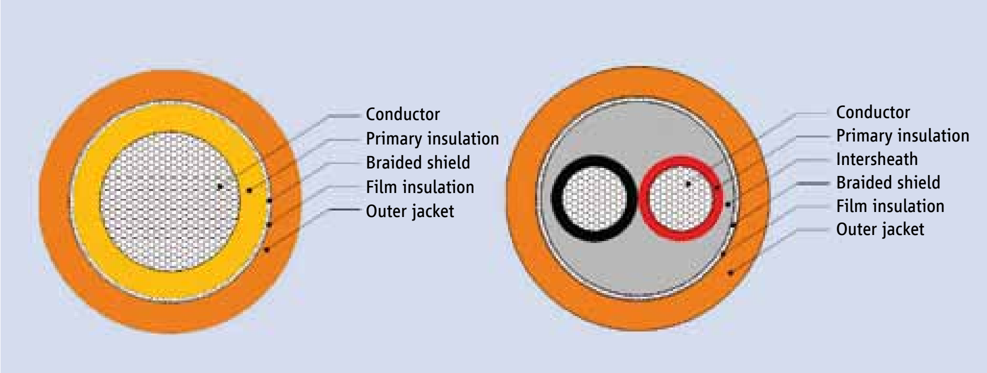
13 Power Distribution

Cables

The key requirement for a vehicle's HV system is the safe transfer of electrical energy. Special HV cables, usually shielded, are used for this purpose. This is necessary for electromagnetic interference and compatibility reasons. Unlike the HF antenna technology, the shield is contacted on both sides and connected to the ground potential. Single-core shielded cables are primarily used within the powertrain – i.e. the two-phase connection of the HV battery to the power distributor and from there the three-phase connection of one or several electric motors. Common cross-sectional areas range between 16 mm² and 70 mm².

Significantly less powerful ancillary components such as air-conditioning compressors, auxiliary heaters and the integration of onboard charging units and vehicle inlets for plug-in vehicles are often supplied with multicore shielded cables with cross-sectional areas between 2.5 mm² and 6 mm². The figure below shows the general design of the HV cables deployed.

Fig. 9: Diagram of Single and Multi-Core Shielded HV Cables



Source: Leoni Kabel

The main design criteria for the cables to be used are voltage level, electric-current-induced heat generation and ambient temperature. For the purposes of creating a national standard, the voltage classes 2 and 3 have been defined in LV 216-2 according to the table below.

Table 6: Voltage classes

Voltage classes		AC		DC
		U_{eff} (U_{RMS})	U_{peak}	U_{DC}
Low voltage	1 (A(*))	≤ 30 V	≤ 42 V	≤ 60 V
High voltage	2	≤ 600 V	≤ 849 V	≤ 900 V
High voltage	3 (B(*))	≤ 1000 V	≤ 1414 V	≤ 1500 V

This table was compiled on the basis of ISO 6469-3.
ISO 6722-1 specifies voltage class 2 with 600 V AC and 600 V DC and does not consider voltage class 3.
ISO 6469-3 groups voltage classes 2 and 3 in class B.

(*) Voltage class specification acc. to ISO 6469-3
U_{peak} Peak voltage
U_{eff} (U_{RMS}) Root mean square (RMS)

Source: Entwurf LV 216-2 draft: 5 May 2013: Screened high-voltage sheathed cables for motor vehicles and their electrical drives

The geometry for shielded HV cables has been specified for each voltage level irrespective of the material. This was necessary to ensure uniform and compatible design of the geometric interface to HV connectors.

Compared to voltage class 2, higher wall thicknesses have been defined for the primary insulation of 1000 V C/1500 V DC cables.

Consequently, the cable's outer diameter has also increased. This means that more material is required which eventually leads to higher costs. Given the great band width of voltage class 2, however, it easily covers the majority of current applications, which means that the voltage level of HV cables has little impact on costs.

The stress in HV cables caused by continuously high current rates is often far more significant. Power loss in a cable increases quadratically with the current across the cable length and hence causes intrinsic heating of the connecting components. In combination with high ambient temperatures, e.g. inside the engine compartment or when routed along the exhaust gas system of hybrid vehicles, high temperatures are quickly reached inside HV cables. This call for the use of temperature-resistant materials for the primary insulation and cable sheath and greater cross-sectional areas of the conductor usually made of copper. Both measures can be regarded as the main cost drivers for HV cables. Aluminium is often used as an alternative to copper conductors to reduce weight and cost.

In summary it can be concluded that high current rates combined with rising ambient temperature are the key cost drivers for HV cables.

14 HV Connectors

If the various product requirements had not been 'bundled', there would be a vast range of different HV connector products available for vehicle HV systems. These requirements have therefore been defined in LV 215-1 [1] by working group 4.3.3 of the German automobile manufacturers. This approach has resulted in the standardisation of HV connectors for use with different vehicle components. More than 50 product requirements have been specified to enable their use under as many application conditions as possible, e.g. max. operating voltage 850 V, electric shock protection according to IPX2B (VDE probe), leading signal contact (HVIL), EMC requirement for 10 A permanent current load via shield. LV 215-1 also classifies HV connectors into different power categories based on cable cross-section and current-carrying capability. Many of these product requirements have a major impact on the design of HV connectors and have so far not been used in this combination [1-6].

The configuration of the socket outlet and charging path of battery and plug-in vehicles is unusual in terms of the standardised design. The on-board charger usually disconnects the on-board HV circuit from the supply system.

Charging Socket Outlet

Charging plugs and sockets are standardised in IEC 62196-1/-2 [6, 7] and classified into three types. All types must withstand 10000 mating cycles under specified pollution conditions. The maximum ambient temperature during charging must not exceed 50°C. To pass the glow-wire test, special additives are required for the socket outlet that adversely affect the processing of the material and its mechanical properties. This is not required for connectors in the vehicle's HV system.

The maximum voltage for the type 2 socket outlet has been specified at 500 V AC. This design enables the transmission of up to 70 A single-phase current or 63 A three-phase current.

Fig. 10: Three-phase plug

Source: Tyco Electronics AMP

The three-phase plug (see fig. 10) connects the type 2 socket outlet with the on-board charger and hence the vehicle HV system with the power supply network (see fig. 11).

Fig. 11: Type 2 charging interface

Source: Tyco Electronics AMP

Fig. 12: Combo charging interface

Source: Delphi Deutschland

14.1 Safety Interlock Connectors

Fig. 13: HV connectors with safety interlock

Source: Leopold Kostal

Some of the many different high-voltage connectors use a safety interlock feature to prevent unmating during load. The reason behind this is the time required by the power electronics' capacitors to reach a safe voltage level. The connectors feature an interlock that ensures contacts can only be touched after a defined time delay. This requirement is no longer demanded by the current LV 215-1.

A holistic system approach must be selected to further optimize future HV connectors and terminals for the vehicle HV system. This approach does not consider connectors as isolated connecting elements between components but includes them in the overall system design. Current derating curves in line with LV 214-1 [8] provide laboratory values that only give an indication of the current carrying capability under real vehicle conditions. Advanced system approaches permit, for example, smaller cable cross-sections and hence weight and cost reductions in the overall system.

Fig. 14: Electric vehicle portable charging cordset

Source: Delphi Deutschland

15 Charge Controller and DC/DC Converter

Battery charging devices, commonly referred to as charge controllers, are used to convert alternating current supplied from the main power grid to the direct current required by the battery. These can be built into the vehicle for up to 7 kW or installed externally in the case of higher power supplies due to their larger dimensions and weight.

More advanced versions are planned that support billing from public charging points.

As illustrated in figure 2 and 3, several voltage levels exist within a vehicle that are connected to bi-directional DC/DC converters. These converters and the charge controllers often require some kind of connection to the cooling system in addition to the actual installation space. To reduce cooling requirements and consequently installation space and installation limitations, highly efficient circuitry concepts will have to be developed over the next few years.

Fig. 15: Battery charger

Source: Leopold Kostal

16 Electric Machine Voltages

Hybrid and electric vehicles are operated with three-phase or multi-phase synchronous or asynchronous or reluctance machines that are adapted to the automotive environmental conditions (humidity, temperature, mounting design, vibrations, pollution, etc.). The following physical principles must be observed for all e-machines:

- The motor's nominal speed determines its nominal voltage or conversely, the faster the machine is required to turn, the higher must be the inverter's control voltage.
- The motor torque is determined by the current rate. This is why the maximum starting torque is limited by the maximum inverter current.
- Increasing the speed while simultaneously increasing the voltage may increase the mechanical performance of an e-machine depending on the motor's mounting design. Conversely, it is possible to use a smaller machine for the same performance requirements if the transmission ratio is increased.

By varying the number of turns, electric machines are adapted to the nominal speed and nominal voltage that can amount to 75% maximum of the (minimum) battery voltage. Traction motors can be designed to enable operation in the 'field weakening range' by drawing reactive power. In this range, e-machines behave like an ideal transmission by supplying constant power while reducing torque with higher speed. Separately excited synchronous motors can weaken the field by reducing the field current without additional application of reactive current.

When the field weakening range is increased, the nominal point of the e-machine shifts to the lower speed range, while the number of turns increases and the current required by the inverter for the necessary starting torque reduces.

E-machines can be adjusted to any supply voltage by changing the number of turns, provided that the wires do not become too thin. However, there is a tendency to use higher voltages for e-machines to reduce the cross-sections of the connecting components and achieve higher speed rates.

Fig. 16: Inverter and DC/DC converter for commercial vehicles

Source: Lenze Schmidhauser

17 Thermal Management

When designing the service life of power electronics, sufficient account must be taken not only of electrical and mechanical stress, but also of thermal stress and especially combined thermal-mechanical stress resulting from interactions between performance and environmental conditions.

There are only two solutions available that ensure appropriate design of components and system for the intended life time:

- Operative system with cooling fluid to actively dissipate heat losses
- Use of robust materials and technologies for sub-assembly components which allow for all inherent temperature-related material properties.

Electric drive cost drivers

The main cost drivers of electric mobility can be found in the field of energy storage. Present-day battery technologies do not allow modest and comparable ranges at acceptable price premiums. In this context, it is not the voltage level that serves as the cost driver but rather the available battery technologies.

On the whole it can be said that in addition to the energy storage costs, overall costs are also influenced by the technical implementation of stationary HV components in the automotive environment. However, it is also important to consider safety aspects and overall efficiency over and above driving cycles. In terms of energy consumption costs, special attention should be given to partial load efficiency.

18 Rules, Norms and Standardisation

Numerous standards apply to electric mobility, including those generated specifically for electric mobility applications. Examples include the standards for type 2 plug and socket systems and for electric cables in road vehicles for voltages above 60 V. There are many other electrical engineering standards that have not been specifically developed for electric mobility but are relevant due to their general nature. These include safety standards and standards relating to installation, for instance.

As part of the activities of the German National Platform for Electromobility (NPE), the DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE) has developed a standardisation roadmap and provided an overview of the relevant standards in the annex of the roadmap. The ZVEI's technical working group on standardisation maintains this list and updates it with information relevant to electric mobility activities. This additional information includes detailed descriptions of the relevant standard's content and status.

19 Safety: Risk Potential Associated with HV Voltages

The prevention of health risks among people involved in the development, manufacture, maintenance or use of products for the HV voltage range has top priority.

Potential risks are:

- Electric energy
- Accidental arcs
- Electric current flowing through the body (electric shock)
- Electromagnetic fields affecting e.g. pacemakers
- Interactions between electric energy and other media

19.1 Effects of Electric Current on the Human Body

Electric current can cause many reactions in the human body, the severity of which depends on the amount of electrical current and the length of time the current passes through the body.

Physiological Effect

The nervous system is affected, resulting in muscle spasms that may prevent the victim from releasing the electrified object, ventricular fibrillation and cardiac arrest.

Thermal effect

The current flow causes burns on the entry and exit points and coagulation of protein in the body.

Chemical effect

The current can cause electrolytic degradation of cells or cellular components which may lead to poisoning of the body.

The symptoms may only be recognizable after a certain time has passed which is why a doctor should be consulted even in the event of a minor accident with HV voltage.

Safeguards must be put in place to prevent the potential risks associated with HV voltage and the resulting damage to humans and animals.

19.2 Electric Safety in Companies

The potential risks outlined above call for special safeguards in manufacturing and industrial companies involved in electric mobility, especially with regard to occupational health and safety.

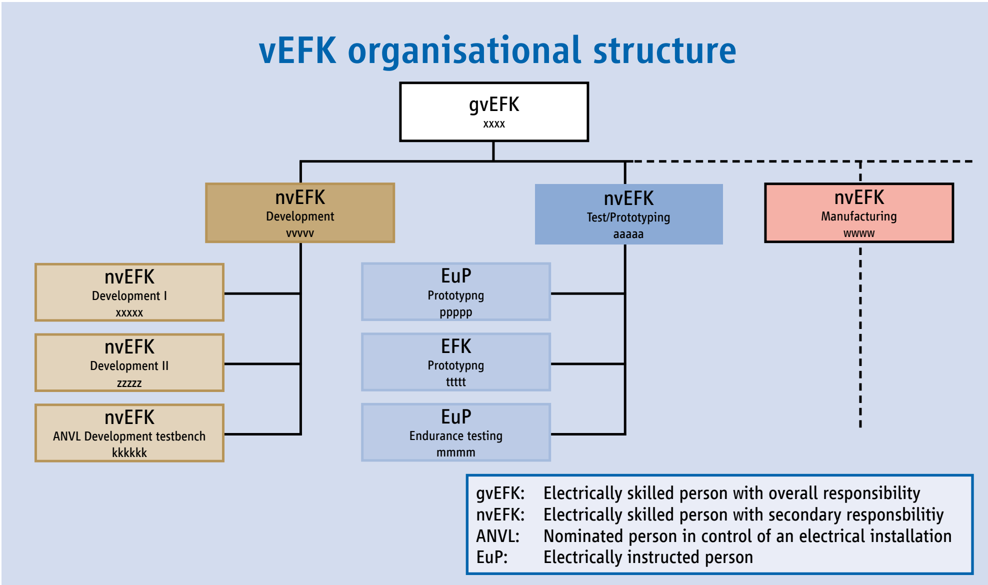
Companies that up until now have been dealing exclusively with low voltages (12 V, 24 V, 42 V automotive products) must adapt their safety requirements to meet high-voltage conditions.

To ensure the appropriate level of protection, it is necessary to observe DIN VDE 1000-100 and DIN VDE 0105-100 requirements detailing the provisions of paragraph 3, section 2 and paragraph 13 of the German Occupational Health and Safety Act (Arbeitsschutzgesetz) and paragraph A3 of the Occupational Health and Safety Regulations of the German trade associations (Berufsgenossenschaftliche Vorschrift für Sicherheit und Gesundheit bei der Arbeit) and to provide a sufficient number of electrically skilled persons and other persons trained to perform defined electrical tasks. The standards presume a chain of responsibility.

Although DIN VDE 1000-100 and DIN VDE 0105-100 are not legal norms, they are of an equally mandatory nature since they are regarded as good engineering practice. By complying with these rules, employers meet their occupational health and safety obligations, which creates legal certainty for the companies.

Workplace and process risk assessments must be conducted for all high voltage areas, e.g. laboratories, production facilities and workshops. Working and operating procedures are then developed on the basis of these assessments, often resulting in the alteration, conversion or extension of laboratory and workshop stations or workplaces to ensure compliance with electrical safety requirements. Further measured that can be taken to increase electrical safety include special marking of high-voltage workplaces and access restrictions for unauthorized personnel, as well as routine training for employees.

Fig. 17: Organisational structure of electrically skilled persons – responsibilities and skills



Source: ZVEI

19.3 Protection Concept

Double protection measures, i.e. protection against direct and indirect contact (ISO 6469-3) are required for protection class B appliances (60 V DC < voltage < 1500 V DC). The concept includes basic protection against direct contact and equipotential bonding against indirect contact. In addition, double or reinforced insulation may be applied.

19.4 Protective Measures

These include design measures that

- are required for live components to provide complete finger safety to IP2xB or personal protection against contact with tool to IP3xD
- impede contact with live parts
- require tools to open locks and enclosures

Key to the design of contact protection for high-voltage appliances are:

- appropriate insulation selected from solid insulation material of < 100 Ω/V DC or > 500 Ω/V AC insulation resistance values
- adequate clearance between live parts and metallic enclosures
- correct dimensioning of creepage distance and air gap

19.4.1 Equipotential Bonding

Equipotential bonding employed for protection against indirect contact requires low-impedance connection of HV appliances with metallic enclosures in the vehicle. The total resistance of the connections must be < 100 mΩ.

Electrical isolation of an appliance's high-voltage and low-voltage areas is another element that completes the protective measures. The potential-free high-voltage system must be galvanically isolated from the low-voltage system. This is achieved by using components suitable for signal, data and energy transmission. The efficiency of the protective measures is verified by measuring the insulation resistance and applying a test voltage.

This must be performed for all high-voltage components!

It is also necessary to mark all high-voltage appliances (lightning symbol in yellow triangle) in compliance with the relevant standards.

19.4.2 Protective Functions

Overcurrent protection must be provided in HV appliances. Energy storage and power electronics must reliably interrupt possible short-circuit currents. Contact with voltages above 60 V DC when opening the contacts must be reliably prevented.

Components that are disconnected from the vehicle HV system must dissipate the energy stored in the component by means of passive discharging and reduce the voltage level to below 60 V DC within the time specified by the OEM.

The system design must ensure that the HV components are voltage-proof according to ISO 6469 – currently common practice:
'The design of the system must ensure that the electric strength of high-voltage components complies with ISO 6469. Exceptions for inverters are currently being discussed.'

19.4.3 Optional Protective Functions

Insulation monitoring is an optional protective function that is not used for each high-voltage component but considered for the high-voltage system. The insulation resistance of the high-voltage systems, AD and DC system, is monitored against vehicle values. In the event of an incipient insulation fault, the vehicle's alert system informs the driver of the fault and requests a service check.

Insulation monitoring devices currently used sporadically will inevitably become an integral part of power electronics or battery management systems and hence their performance.

The detection of an open high-voltage circuit is another optional protective feature. An HV interlock prevents the opening of an energised HV circuit by signalling the HV circuit opening to the central control unit (battery control unit) via a leading low-voltage signal contact in the connector. The central control unit switches off the HV system and stops the energy supply before opening the HV contacts.

20 Life time

Compared with components used in conventional vehicles, those used in electric vehicles also require changes to power electronics which have an impact on their life time. These changes are due partly to the increased operating time of individual systems and partly to load differences with the HV components used.

As far as operating time is concerned, the most important differences concern the charging system and the battery management system (BMS).

While the charging system of a conventional vehicle is expected to operate for approximately 8000 hours, the on-board charging systems in electric vehicles are continuously active when the vehicles are 'hooked up'. According to current estimates, they operate for approximately 30000 hours. The charging unit is expected to operate on standby for a further 60000 hours.

Table 7: Life time restrictions

	Stationary	Vehicle		
		commercial vehicle/bus	passenger vehicle	
Life time (calender-based)	10	15	15	Years
Operating hours	30000	60000	8000	h
T_{min}	-40	-25	-25	°C
T_{max}	70	85	85–120	°C
$^{\Delta}T$	110	110	110–145	K
Vibration	none	2–10 g, sometimes up to 30	2–10 g, sometimes up to 30	

Source: ZVEI

The battery management system is required to permanently monitor the status of the battery. An operating time of 80000 hours is assumed for battery monitoring purposes. Unlike the power electronics used in the electrical drive, it can be assumed that those used in the BMS will operate at a reduced temperature range. This system is helped by the fact that, on account of its electro-chemical properties, the temperature of the battery must be controlled, which significantly restricts the operating temperature range of the entire system encompassing battery and battery management system.

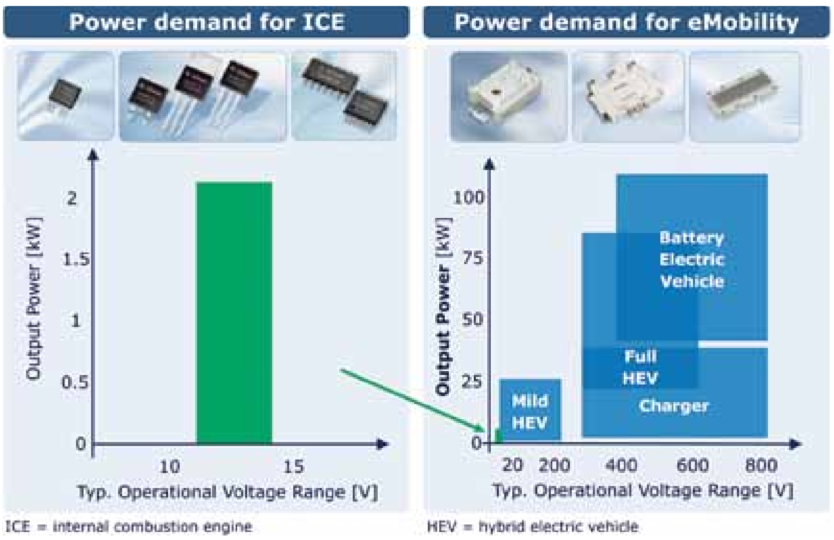
Commercial vehicles have operating times of at least 50000 hours. Consequently the requirements for the powertrain, including the battery, in lorries and buses are significantly higher than for passenger vehicles, whilst the requirements for the battery management and charging system are more or less the same. However, the load profiles of commercial vehicles are very different from those of passenger vehicles; the maximum continuous engine power is higher and they run at maximum output for substantially longer periods; these factors too must be taken into account.

The fundamental differences between the power electronics load of electric vehicles and conventional vehicles is explained below.

Fuel is put into the tanks of conventional vehicles, combusted along with oxygen in the engine and converted to mechanical and thermal energy. This is a chemical-thermal-mechanical energy transfer mechanism. The vehicle electronics here play only a secondary role of optimising the operating conditions. In electric vehicles, the electrical energy comes from the battery and is converted into mechanical energy in the electric motor. This is an electric-mechanical energy transfer mechanism. The entire volume of energy 'flows' via electric actuators. The power electronics required to achieve this are therefore of an entirely different magnitude.

Life time considerations must therefore take account of these new, re-dimensioned power components and their specific packaging and assembly technology (e.g. thermal requirements with respect to powerful vibrations).

Fig. 18: Comparison of power categories



Source: Infineon Technologies

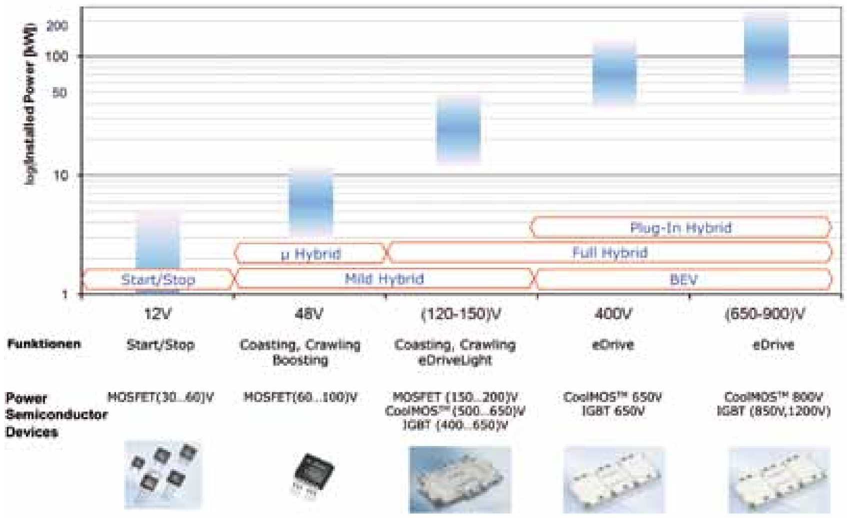
Apart from failures which arise in connection with voltage (flashing/arcing due to insufficient clearance and creepage distances) and electricity, special consideration is to be given to specific failure mechanisms caused by thermal loading as described in the Thermal Management section.

As far as failure mechanisms in power semiconductors are concerned, as already indicated, it is particularly important to consider composite materials made from different metals, metal alloys, ceramics for insulation, silicon used in the actual circuit breaker etc. If one considers the different expansion coefficients it soon becomes clear that the temperature changes arising from power loss when switching the semiconductor components and from the electrical resistance of the materials can result in considerable thermo-mechanical stresses within the composite material.

Whether and to what extent this will result in failures depends largely on the thermo-mechanical stress exerted on the components and the packaging and assembly technology.

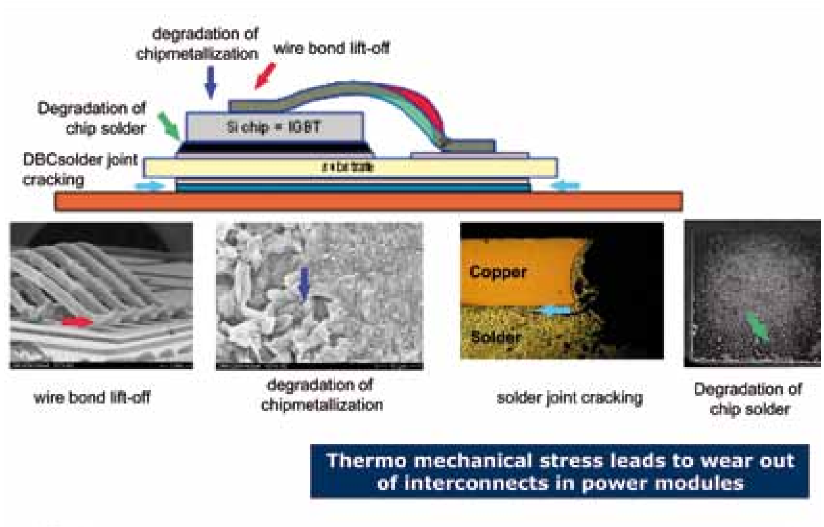
Consequently maximum temperature and load cycle limits are set. These in turn depend on the drive profile and cooling characteristics of the system.

Fig. 19: Power components/modules and power categories of power electronics



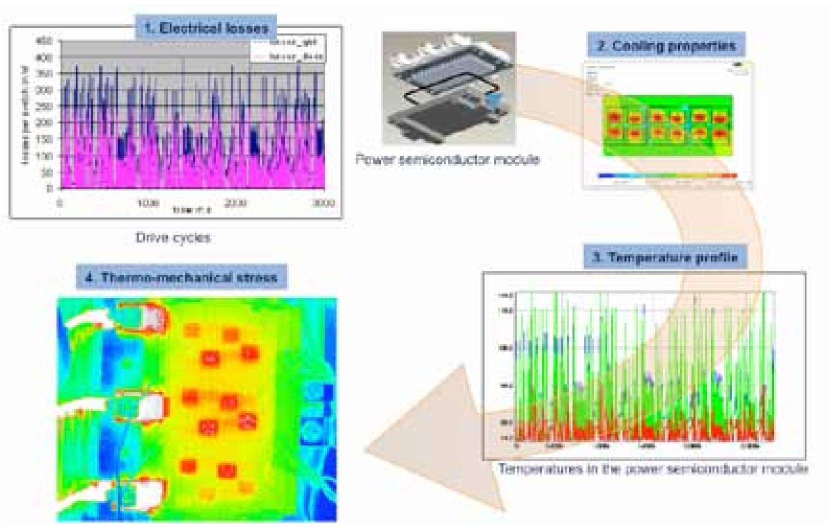
Source: Infineon Technologies

Fig. 20: Causes of failure in power modules



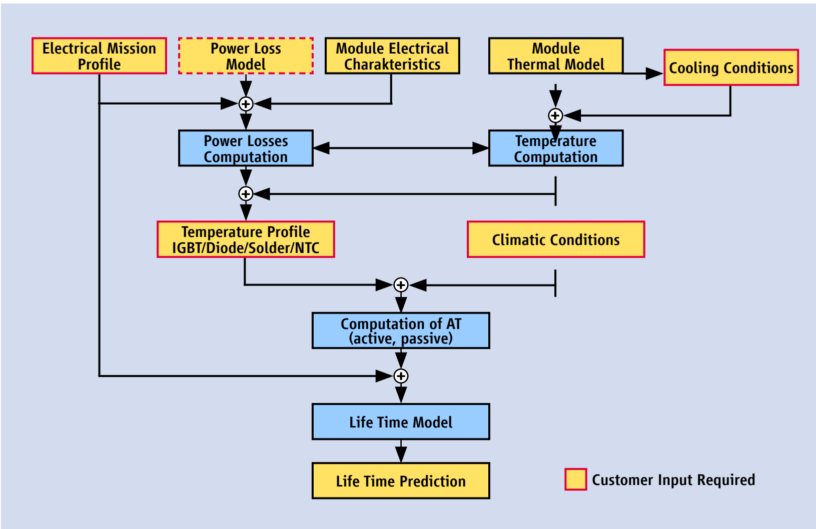
Source: Infineon Technologies

Fig. 21: From drive profile to thermo-mechanical stress in power electronics



Source: Infineon Technologies

Fig. 22: Model to predict life time



Source: Infineon Technologies

Limited installation spaces in vehicles mean that electronics operate at comparatively high temperatures, which presents a major challenge for the life time of the large electrolytic capacitors in charge controllers. Furthermore, strong vibrations expose them to a further high load which must be overcome by fastening the capacitor body to its own housing and mounting the housing on the board, since encapsulating or glueing the capacitors after installation should be avoided on grounds of costs.

An understanding of the failure mechanisms, the requirement profile and the system design is essential in order to make life time predictions. This is nothing new. The difference here, however, is the novel combination of 'in-car power components'. Although these components are already used in train electrical drives and on large production lines, for example, the requirement profiles for these applications are transferable to vehicles only to a limited extent. Furthermore, the vehicle industry has different requirements in terms of unit numbers and costs, which in turn affect system design.

Complex interactions between load profile, system design and failure mechanisms make it very difficult to accurately predict life time. However, statements about life time are an inherent part of the development process. Thus modelling software which takes into account input variables for specific vehicle models is used to perform the task of life time predicting'. This is the only way to obtain reliable predictions about life time.

21 Outstanding Issues

21.1 Further Optimisation Parameters

Up until now, electrical components have not been designed for optimised minimum construction volume and weight. In vehicles, however, such minimal dimensions are indispensable. In the coming years, development work must therefore focus on size optimisation measures to enable us to retain our international competitiveness.

22 Outlook and Summary

Future mobility (road transport) will be determined by electrical drive concepts, be it hybrids of all types or all-electric cars. In conjunction with this, new voltage levels beyond the current 12/24 V will be adopted in our vehicles. Electric power transmission plays a vital role throughout the entire system in hybrid, fuel cell and battery-powered vehicles. Widely varying requirements are placed on HV components, depending on the system design.

Today, all sectors of vehicle development place strong emphasis on the controllability of these innovations. Realistically, all the necessary technologies are already available – the task now is to integrate these into the automotive environment safely and reliably. This is an evolutionary process which will improve with every application and ultimately provide the necessary degree of component standardisation which in turn will also reduce product costs.

Nevertheless, the automotive environment will have to adapt to the new conditions in terms of development and manufacturing, as well as operation and service. It is clear that there is still some work to be done with regard to our approach to dealing with electric drives and the issues they raise: providing appropriate expertise and meeting the training needs of our experts. The Technical Working Groups of the ZVEI Electromobility Competence Centre will play an active role in this process.

Furthermore, the automotive industry will have to work with energy companies and charging point providers, since electromobility requires the generation and provision of electrical energy, be it within the necessary infrastructure (grids) or using bidirectional storage concepts (super grids). Further research is clearly needed in this area. Electromobility has an exciting future ahead and will occupy our engineers for many years to come as they endeavour to create a future world in which we can manage without fossil fuels.

23 Appendix

23.1 Semiconductor Materials for Packaging and Assembly Technology

The impact and importance of materials increases as power density, switching frequencies and reliability requirements increase. Standard power electronics modules primarily use solder joints with lead-free SnAg (previously also known as SnPb/Ag) or wire bonding with thick aluminium wires for PCB packaging and assembly. These materials and the corresponding process are well-established and have been used successfully for many years.

However, PCB packaging and assembly materials are reaching their limits as a result of increasingly higher power density and operating temperatures (150°C, 175°C and higher) and the demand for improved power cycle and long-term reliability (more than 15 years for automotive applications). Substantial temperature differences, e.g. during a cold start in the winter, pose another challenge to power cycle reliability.

The use of new semiconductor materials such as SiC or GaN further increases the requirements for PCB packaging and assembly materials. These semiconductors enable significantly higher switching frequencies, reduced switching losses and higher power densities while working reliably at considerably higher barrier layer temperatures. Due to its excellent thermal conductivity, SiC is also suitable for higher voltage classes and power densities.

All these reasons fuel the need for optimised materials with improved mechanical, thermal and electrical properties.

23.1.1 New Solder Alloys

A wide variety of projects have focused on improving the thermal cycling reliability and high-temperature properties of solder alloys, especially in view of the transition to lead-free soldering processes. The main challenge encountered in these studies was to achieve the intended high-temperature properties of the solder joints while keeping the soldering temperature low enough (stress on components, base substrates, etc.). Simply increasing the melting point does not achieve the desired outcome.

Examples include special alloys such as the 6-element system SnAgCuBiSbNi (also referred to as InnoLot® according to the project) and the HT1 alloy (SnAgCuIn + crystal modifier). The melting point of these two new alloys is similar to SnAg solder and they support improved thermal cycling and high-temperature properties. Consequently, the maximum permissible operating temperature can be slightly increased for module-level power electronics and their power cycle reliability moderately improved.

23.1.2 Diffusion Soldering

The high-temperature properties can be significantly improved with isothermal solidification of the solder (diffusion soldering).

Conventional solder connections show a eutectic zone in the centre of the solder joint and the isothermally solidified intermetallic zones towards the metal. The eutectic zone of traditional solders determines the thermomechanical properties. Its melting point with SnAg solder is 221°C and with SnPb solder 183°C.

However, during diffusion soldering (thin layers of less than 10µm), the solder (e.g. SnCu, melting point 227°C) completely solidifies isothermally into the intermetallic phase. These intermetallic phases have a significantly higher melting point than the traditional solder itself: Cu3Sn phases 676 °C and Cu6Sn5 phases 415 °C. Special DCB substrates of low surface roughness must be used for thin layers; a standard DCB substrate has a surface roughness of approx. 20 µm.

For thicker layers, a base material, e.g. copper, is added to the diffusion solder. The molten solder diffuses into the base material until the entire solder gap has solidified isothermally.

The solder must be kept molten during diffusion soldering processes until the solder gap has completely solidified due to diffusion. This liquid phase is significantly longer than during standard soldering processes, especially for thick layers. Premature interruption of the diffusion soldering process would result in a residual eutectic zone and adversely affect the mechanical properties. The main challenge for thicker layers is to achieve a homogenous, void-free solder joint.

23.1.3 Silver sintering

Low-temperature silver sintering significantly improves the high-temperature properties and the power cycle reliability in particular.

The thermal and electric conductivity of the silver sinter layer and the temperature resistance (Ag melts at 961°C whereas SnAg solder melts at 221°C) are considerable higher.

In addition, the use of sinter paste supports thermal conductivity values of 200 W/mk and above.

The sintering process differs from the solder process:

- Soldering: the application of heat (230–250°C for SnAg solder) causes the solder to melt, diffusion processes occur in the adjacent metal and intermetallic phases are formed. Vacuum soldering helps to minimise the formation of voids. Flux residue is washed off after the soldering process.
- Sinter paste: the application of heat (5–30 MPa, subject to the IGBT/diode surface) causes the silver particles to compact due to diffusions processes. Pressure sintering helps reduce the porosity especially of semiconductors that have a large surface. No extra cleaning is required after the sintering process.
- Sintering adhesive: the application of heat hardens the adhesive and the silver particles are sintered. In this case, neither pressure nor cleaning after the hardening is required.

The sinter adhesive combines the benefits of fusion bonding of Ag sinter pastes and the high adhesion forces of Ag conductive adhesives in a paste system. Since sinter adhesive is more flexible compared to solder, it can better compensate the thermomechanical stress created by the differences in the CTE of the substrate and the semiconductor. This can be particularly relevant for larger semiconductors. The sinter adhesive has a lower thermal and electric conductivity than sinter paste. Operating temperatures of up to 200°C seem to be manageable with sinter adhesives.

Sintered paste connections have remained thermomechanically reliable even at extremely high temperatures such as 300°C.

23.1.4 Bonding Wires and Bonding Ribbons

Improved temperature resistance and power cycling reliability, e.g. with sintering, also requires optimisation of the bonding wire connection. Ultrasonic wedge bonding is a standard process using aluminium wire up to 500 µm thick.

While power cycling reliability can be somewhat improved using aluminium ribbons, substantial improvement can be achieved with Cu wires and ribbons. The thermal conductivity of copper is considerably higher than that of aluminium.

23.1.5 Tensile Strength

Typical Bonding Strength (Ø 300 µm)
Increased bonding forces are required for copper due to its higher tensile strength and hardness.

Aluminium-coated bonding wires and ribbons with a copper core provide a compromise:

- The aluminium coating makes these bonding wires much easier to process than pure Cu wires.
- The copper core improves the thermal, electrical and mechanical properties and hence the power cycling reliability compared to pure Al wires.

23.1.6 Chip, Substrate and Leadframe Surface Finishes

The use of new materials such as silver sinter paste or Cu bonding wires also means that the surface finishes of the semiconductors, substrates and leadframes must be adapted to these processes. Sinter pastes are currently used primarily on Ag, Au and Pd surfaces. As part of the ProPower project, new functional surfaces based on copper and the relevant pastes are also being developed.

24 List of Abbreviations

AC	Alternating Current
ASC	Active Chassis Control
Batt	Battery
BEV	Battery Electric Vehicle
BMS	Battery Management System
CHAdeMO	Multi-brand electric interface of a battery management system for electric cars developed in Japan (charge de move)
COD	Chemical Oxygen Demand
DC	Direct Current
E/E	Electric/Electronics
EM	Electric Motor
EMC	Electromagnetic Compatibility
EPS	Electric Power Steering
EV/BEV	Electric Vehicle / Battery Electric Vehicle
FC	Fuel Cell
WSD	Windshield defroster
HEV	Hybrid Electric Vehicle
HV	High Voltage
HVIL	High Voltage Interlock Loop
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
IT	Isolated Terra
IPX2B	Electric Shock Protection Standard
ISG	Integrated Starter Generator
ISO	International Organisation of Standardisation
kW	Kilowatt
kWh	Kilowatt hour
PE	Power electronics
LV	Low Voltage
LV 216	Delivery specification (of OEMs) 216
M	Electric machine (motor)
M/G	Motor/Generator
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
Nm	Newton Metre
NPE	National Platform Electromobility
RE	Range Extender
RMS	Root Mean Square
SiC diode	Schottky diode has no p-n junction (interface between two types of semiconductor material), but a metal-semiconductor junction (barrier)
TF	Task Force
vEFK	Electrically skilled person responsible
CTE	Coefficient of Thermal Expansion
Wh/kg	Watt hours per kilogram, energy density per weight
Wh/l	Watt hours per volume, energy volume, energy density per volume
V	Volt

25 Further Reading

- 'ProPower' research project – Compact electronic modules with high power for e-mobility, funded by the BMBF, ref. 523
- Novel silver contact material for applications on DCB, Yvonne Löwer, Thomas Krebs, Susanne Duch, Sebastian Fritzsche, Wolfgang Schmitt, Muriel Thomas, PCIM 2012
- Study on sinter technology connections (Sinter Kontaktierung mit Sintertechnologien) by Wolfgang Schmitt, Sebastian Fritzsche, 2013

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[2] IEC 60529 (DIN 40050-9): Degrees of protection provided by enclosures (IP Code), October 1991

[3] IEC 60664-1: Insulation coordination for equipment within low-voltage systems, January 2008

[4] ISO 6469-3: Electrically propelled road vehicles – Safety specification – Part 3: Protection of persons against electric shock, November 2010

[5] LV 216-2: Screened high-voltage sheathed cables for motor vehicles and their electrical drives, June 2011

[6] IEC 62196-1: Plugs, socket-outlets, vehicle couplers and vehicle inlets – Conductive charging of electric vehicles Part 1: General requirements, October 2011

[7] IEC 62196-2: Plugs, socket-outlets, vehicle couplers and vehicle inlets – Conductive charging of electric vehicles Part 2: Dimensional interchangeability requirements for pin and contact tube accessories, May 2010

[8] LV 214-1: Vehicle connectors – Test specification, March 2010

[9] http://www.iso.org/iso/mou_ev.pdf

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