LAPIN AMK
Lapland University of Applied Sciences

HIGH VOLTAGE COMPONENTS IN COMMERCIAL VEHICLES

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Thesis
Technology, Communication and Transport
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Opinnäytetyön tiivistelmä

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Opinnäytetyön tavoitteena oli selvittää, minkälaisia vaatimuksia ajoenergian siirtoon ja varastointiin käytetty korkeajännite asettaa hyötyajoneuvojen johdinsarjoille komponentteineen sekä sähkökeskusten toimilaitteille. Opinnäytetyössä käsiteltiin sähköajoneuvojen mukanaan tuomia haasteita ja mahdollisuuksia sekä jännitetasojen eroavaisuuksia teollisuus- ja ajoneuvopuolella. Lisäksi käsiteltiin lyhyesti erilaisia latausmetodeja sekä alan standardisointia. Työ tehtiin PKC Wiring Systems Oy:lle.

Korkeajännitejärjestelmässä käytettäviä komponentteja ja niiden ominaisuuksia käsiteltiin siten, että lopputuloksesta muodostuu yleiskäsitys uusista vaatimuksista. Keskeisimpänä ominaisuutena olivat henkilöturvallisuusnäkökohdat sekä suunnittelussa ja materiaalivalinnoissa huomioonotettavat asiat toimittaessa korkeajänniteympäristössä.

Yrityksen sisäiseen käyttöön tarkoitetussa osiossa laadittiin lyhyt tekninen analyysi korkeajännitekomponentteja sisältäneistä tarjouskyselyistä. Näiden pohjalta tehtiin ehdotuksia mihin osa-alueisiin tulisi panostaa, mikäli jatkossa halutaan suunnitella ja valmistaa korkeajännitetuotteita.

Opinnäytetyön tulokseksi saatiin riittävät lähtötiedot ymmärtää korkeajännitekomponenttien suunnittelussa ja valmistuksessa huomioitavat asiat.

Avainsanat sähköajoneuvot, korkeajännitekomponentit ja materiaalit ajoneuvoympäristössä, suunnittelusäännöt

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Abstract of Thesis

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Author	B.Sc. Matti Turska	Year	2017
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The main goal of the thesis was to find out what kinds of requirements commercial electrical vehicles set to wiring harness components and electrical centres. The document presents basic structures of the electrical vehicles, charging methods, standardization and the main challenges of the electrically propelled vehicles. It also compares differences of the voltage levels in automotive and industrial segments.

This thesis represents main power distribution components like wires, cables, connectors, fuses and relays used in a high voltage automotive electrical system. An electrical safety concern in an automotive high voltage environment starts from human safety issues continuing to design rules and safety features in a vehicle. Design considerations bring up facts about how high voltage affects different materials, introduces some selected printed circuit board design rules and other things, which need to be taken into account with high voltage systems.

The company version also includes a technical overview about request for quotations, which are focused on electrical vehicle segment. The short summary points out improvements needed from the design point-of-view to continue in this area. This chapter is intended for PKC Group's internal use only.

As an outcome, this thesis work provides needed knowhow for understanding the basic challenges and details needed to be considered in high voltage component design and production inquiries.

Key words electrically propelled vehicles, automotive high voltage components and materials, High voltage design rules

CONTENTS

SYMBOLS AND ABBREVIATIONS

AWD	All-Wheel Drive
CHAdeMO	CHArge de MOve
CTI	Comparative Tracking Index
EV	Electrical Vehicle
FC	Fuel Cell
FCA	Fiat Chrysler Automobiles
FR	Flame retardant
GF	Glass fiber
GFCI	Ground Fault Circuit Interrupter
GM	General Motors
HEV	Hybrid Electric Vehicle
HVIL	High Voltage Interlock Loop
HVPF	High Voltage Polyimide Film
ICE	Internal Combustion Engine
IC-CPD	In-Cable Control- and Protecting Device
IMD	Insulation Monitoring Device
KL15	Klemme (In German) / Clamp
LEV	Light Electric Vehicle
MELF	Metal Electrode Face
OEM	Original Equipment Manufacturer
PA	Polyamide
PBT	Polybutylene Terephthalate
PCB	Printed Circuit Board
PDU	Power Distribution Unit
PESU	Polyethersulfone
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Performance Level Categories
PPSU	Polyphenylsulfone
PSU	Polysulfone
RCD	Residual Current Device
RE	Range Extender
RESS	Rechargeable Energy Storage System

RFQ	Request for Quotation
TEM	Transverse electromagnetic
TPU	Thermoplastic polyurethane
V2G	Vehicle to Grid
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie e.V. / Central Association of the Electrical Engineering and Electronics Industries e.V.

1 INTRODUCTION

The European Union has a political target to create market for electrical vehicles. At the same time, car manufacturers see hybrid and electrical vehicles as the next big step in the automotive industry. End-users are motivated and interested in environmental friendly alternatives as well as low consumption vehicles. (Sahkoinenliikenne.fi.)

The main purpose of the thesis is to gather available information to same place concerning high voltage components in commercial vehicles. The idea is to summarize the requirements and provide a basic understanding, which helps to quote and design wiring harnesses, junction boxes, fuse and relay centers and even smart electric centers in the future.

In automotive engineering high voltage is defined as a voltage within a range of 30–1000 V_{AC} or 60–1500 V_{DC} (UNECE 2013). The components in this thesis mean wiring harnesses, electric centers, electric control units as well as separate wires, housings, terminals, fuses etc. A commercial vehicle means any type of a motor vehicle used for transporting goods or paid passengers (Council Directive 1985). The term can and usually also is expanded to mean agricultural vehicles such as tractors and forestry machines like harvesters. In addition, construction equipment like earthmovers, excavators and dumpers are considered as commercial vehicles.

Before starting this thesis work the biggest technical questions concerning RFQs including High Voltage were; what kind of components we can use and what are the differences comparing to the existing ones? What needs to be taken into account when higher voltages are used? Is it safe to test them firstly in a R&D phase and naturally later on in a production phase? What electrical and mechanical limitations and possibilities there are when high voltages are introduced? Do we know enough about standardization and legal requirements?

This thesis work focuses on vehicle power supply lines, connection points and electrical protection in commercial vehicles. The purpose is not go through different energy storages, battery management systems, motor techniques and all other devices, which exists on hybrid and electrical vehicles. This due to the fact that there is a lot of knowledge available in a general level on the Internet and these components are not relevant for the company the thesis work was done for. The aim is also not to argue if it is reasonable or not to use electric vehicles.

The outcome of the thesis will answer the main questions described earlier in this chapter and give some ideas and suggestions what shall be investigated for being considered as a serious design partner and manufacturer for automotive components including high voltage. Ideas for a new thesis work topics are also introduced which can then go deeper and concentrate more on some specific areas.

2 BACKGROUND

The main target for the electrification and hybridization of the commercial vehicles is fuel saving and reducing emissions. A short-term solution to reach this is optimization of the conventional drives as diesel and gasoline. Together with that, manufacturers are developing motors, which use alternative fuels as well as hydrogen drive and fuel cells. Hybridization is not just adding an electrical motor to be part of a vehicle. It can be combined with different fuels and types of the drives. There are also different types of the functions e.g. regenerative braking systems, start/stop –functions, DC/DC converters, downsizing of combustion engine and roll-mode. The highest fuel saving potential in a city traffic can be reached in light commercial vehicles, delivery trucks and city busses. (Hellwig, 2-3.)

Main hybrid structures in commercial vehicles can be divided into three main groups: Series, Parallel and Power-split hybrids (Hellwig, 4). The main principles of the different HV systems are shown in Figure 1.

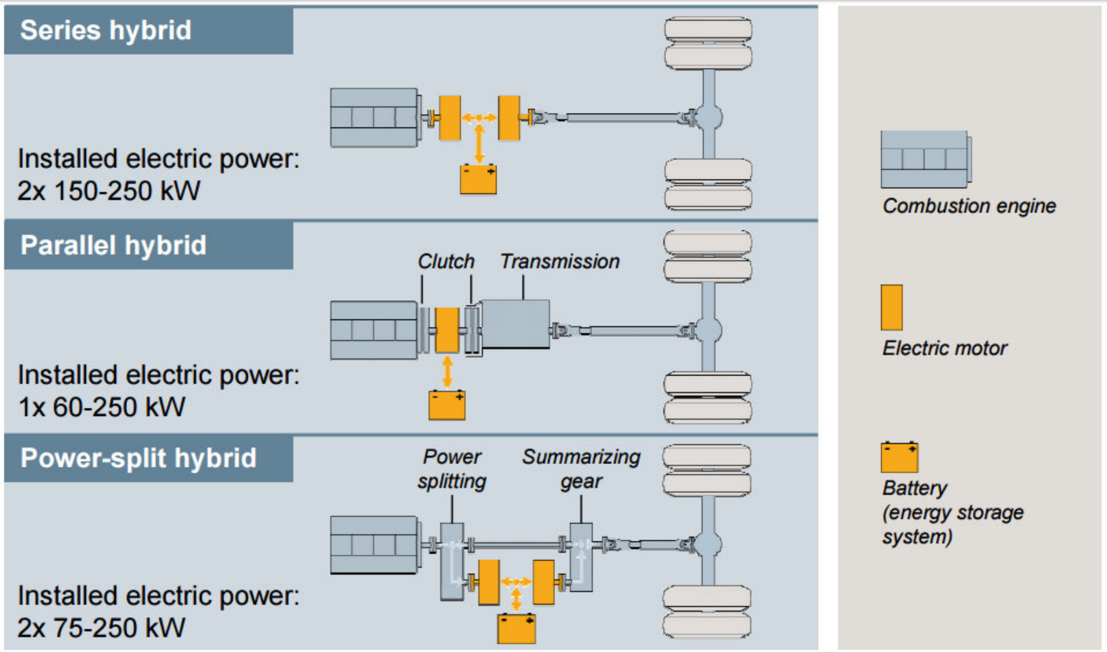


Figure 1. Main Hybrid Structures (Hellwig, 4)

(Hybrid-) electric vehicles are equipped with a separate high voltage (HV) power and ground system that is fully isolated from the standard vehicle (24 V) power and ground. The voltage level of the HV system is not standardized and can differ for each vehicle type (generally the voltage will be in the range of 400~800 V for heavy-duty vehicles; status 2012). Besides the HV system (AC and DC), each electrical vehicle (EV) will have a low voltage system (24 V_{DC}) too, to power the standard vehicle systems and functions. (DAF 2012.)

2.1 Series Hybrid

Series hybrid technique allows pure electric traction by batteries either pure internal combustion engine (ICE) traction by engine to generator. It is possible to use both at the same time. The engine to generator solution can propel the vehicle and charge batteries at the same time. Regenerative braking system allows electric motor to charge batteries. (Bradley & Stanton.)

The mechanical decoupling of the engine from the drive wheels allows operation anywhere on its speed-power curve. Electric motors spin to very high rpm and therefore the transmission unit is cheaper and lighter because it requires less gear. This solution provides possibility to use one electric motor per wheel, which allows new implications for all-wheel drive (AWD), traction and stability control. All in all, control systems are relatively simple. (Bradley & Stanton.)

As disadvantages of the series hybrids ICE energy needs to convert twice (mechanical to electrical to mechanical) and therefore losses can be significant compared to parallel hybrid. Solution requires a generator, which adds cost and weight. It also requires a large electric motor since it is the only power plant directly propelling the vehicle. If the battery does not have a high storage capacity, it requires a full-sized ICE. (Bradley & Stanton.)

2.2 Parallel Hybrid

Parallel hybrid is propelled by batteries at low speed and it has pure ICE traction. Naturally, it is possible to use both at the same time. Regenerative braking system is similar as in series hybrid solution. Battery charging is also possible when ICE propels the vehicle. Electric motor can charge batteries at the expense of the ICE. (Bradley & Stanton.)

Speed and torque of the two power plants can be chosen independently (within constraints). The power plants can be smaller, and therefore cheaper and more efficient. As a disadvantage parallel hybrid is more complex than series – in particular, control is far more complex. (Bradley & Stanton.)

2.3 Power-split Hybrid

Power-split hybrid system is sometimes also called as series-parallel hybrid. Pure electric traction by batteries at low speed and pure ICE traction are possible modes as well as both can propel vehicle at the same time. Regenerative braking and battery charging with or without ICE is possible. (Bradley & Stanton.)

The system combines the advantages of a Series and a Parallel. It has direct mechanical path for the ICE, which is very efficient in steady operating conditions like cruising. It has also an electromechanical path, which allows the efficient operation of the ICE in unsteady driving, such as speed variations seen in city driving. The disadvantage is further complexity and cost. (Bradley & Stanton.)

2.4 Voltage Levels in Automotive

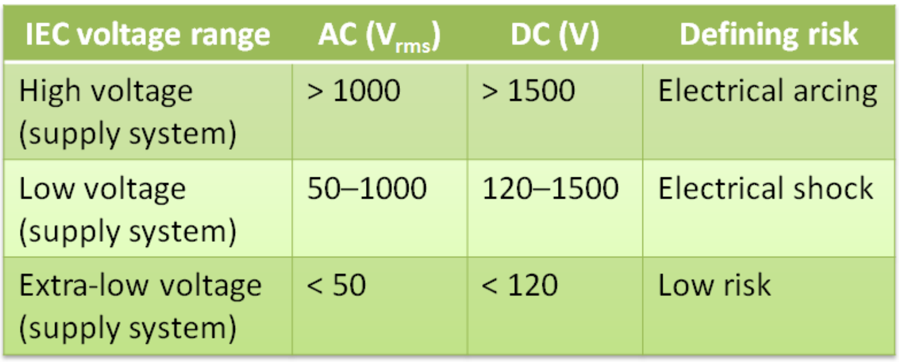
In automotive engineering, “high voltage” is defined to be within a range of 30 – 1000 V_{AC} or 60 – 1500 V_{DC} (UNECE 2013). Voltages under 30 V_{AC} and 60 V_{DC} are defined as “low voltage.” ISO 6469-3 presents voltages in a similar way, but defines also classes A (Low voltage) and B (High voltage).

LV 112-1 presents three voltage classes, which are based on ISO 6469-3 class A and B:

- Low voltage class 1: $\leq 30\ V_{AC}$ and $\leq 60\ V_{DC}$
- High voltage class 2: $\leq 600\ V_{AC}$ and $\leq 900\ V_{DC}$
- High voltage class 3: $\leq 1000\ V_{AC}$ and $\leq 1500\ V_{DC}$

The international standard IEC 60038 refers to three voltage ranges (Table 1). It shows that there are differences in nomenclature when speaking of “automotive electric” and “industry electric”.

Table 1 Voltage levels according to IEC 60038 (IEC 60038, 2002)



IEC voltage range	AC (V_{rms})	DC (V)	Defining risk
High voltage (supply system)	> 1000	> 1500	Electrical arcing
Low voltage (supply system)	50–1000	120–1500	Electrical shock
Extra-low voltage (supply system)	< 50	< 120	Low risk

Low voltages in the automotive industry have been traditionally divided into 12 V_{DC} and 24 V_{DC} systems. There has been discussion about 36 V_{DC} and 42 V_{DC} systems but nowadays it seems that 48 V_{DC} systems will be the next selection and a rather big step in the automotive industry.

Figure 2 shows the base architecture of 12 V_{DC} – 48 V_{DC} systems. According to that, there will be two separate systems in vehicles and it seems that the loads having higher power consumption will be placed under 48 V_{DC} systems.

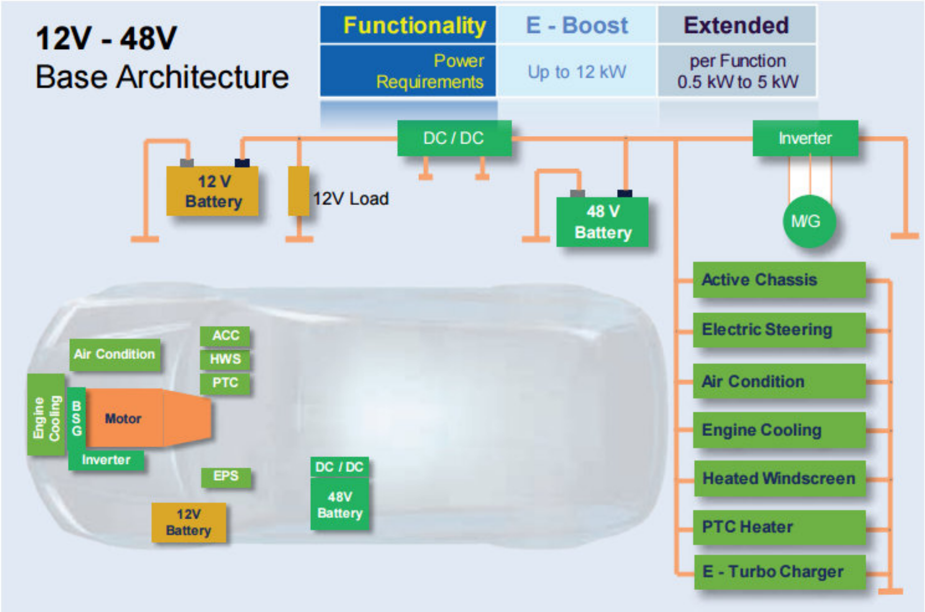


Figure 2. Base architecture (ZWEI.org 2016 source: Delphi)

12 V_{DC} systems are widely used in passenger cars and also in commercial vehicles in North America. Otherwise, the 24 V_{DC} system is the most common in commercial vehicles.

2.5 Why to use High voltages?

Nowadays 24 V_{DC} electrical systems are widely used in commercial vehicles. Electrical motors have high power consumption. For example, Volvo I-SAM power output is 150 kW (Volvo Bus Corporation 2014a). According to the available material (Volvo Bus Corporation 2014c) the output DC voltage in this motor is between 0 - 750 V_{DC}.

In a 24 V_{DC} system, this would mean current as high as 6250 A.

$$I = \frac{P}{U} = \frac{150\ kW}{24\ V} = 6250\ \text{A} \quad (1)$$

As an example, the biggest commercially available bolt-in (mega) fuse is rated up to 500A at 70V_{DC} (Littelfuse). Exide battery model EF2353 12 V has 235 Ah capacities (Exide 2015). If we consider one hour full power driving, it would require 54 pcs of the batteries to be used in a vehicle: (2 x (to reach 24 V_{DC} voltage level) 27 pcs x 235 Ah= 6345 Ah in 24 V_{DC} level). The weight of the one battery is 57.5 kg and multiplying this by 54 pcs means 3105 kg as an extra mass to the vehicle.

The required wire cross-section (mm^2) with a 4% voltage loss can be calculated using the following formula:

$$u = b\left(\rho_1 \frac{L}{S} \cos\varphi + \lambda \times L \times \sin\varphi\right) I_B \quad (2)$$

u = Voltage drop
b = factor **2** for single phase circuits
ρ_1 = Resistivity of the conductors in **Ωmm^2/m**. For copper this value is 0.017241 (IPC-TM-650, 3)
L = Length of the wiring system in **m**
S = Cross section of the wiring system in **mm^2**
I_B = Operating current of the wiring system in A
For DC circuit Cosφ = 1 and Sin φ = 0

Cosφ = Power factor = 1 for pure resistive load, <1 for inductive charge (usually 0.8) (for DC circuit Cosφ = 1)
Sin φ = acos (Cosφ) (for DC circuit Sinφ = 1)
λ = Linear reactance of the conductors in mΩ/m

Simplified formula 2 looks like that:

$$u = 2\left(p_1 \frac{L}{S}\right) I_B \qquad (3)$$

Solving cross-section S:

$$S = \frac{2(p_1 L) I_B}{u} \qquad (4)$$

u_{loss} = 4% voltage loss about 24 V is 0.96*24 V = 23.04 V

ρ_1 = 0.017241 Ωmm^2/m
L = 5 m
I_B = 6250 A

Calculating with these values the required cross-section of the cable would be: S= **1077.5 mm^2**.

The thickness of the cable can be calculated using the formula:

$$d = \sqrt{\frac{4A}{\pi}} \qquad (5)$$

where

A = S = 1077,5 mm^2
d = 37 mm. (Thickness of the cable)

Re-calculating with 750 V instead of 24 V (using formula 1) the maximum current I drops to **200 A.**

I = 150 kW / 750V = 200 A

4% voltage loss of 750 V would be 30 V (u_{loss}=0.96 * 750 V=720 V), which cannot be accepted. So, let us use the same 1 V loss, which was used in 24 V system calculations.

$$S = \frac{2(p_1 L) I_B}{u} \qquad (4)$$

ρ_1 = 0.017241 $\Omega mm^2/m$
L = 5m
I_B = 200A (earlier 6250A)
S = **34.5mm^2** (instead of 1077.5 mm^2)

Using formula 5, the thickness of the cable (d) will be only **6.6 mm** (instead of 37mm). Weight of a 5 m long cable in a 24 V system can be calculated as following:

$$m = \rho_{Cu} *((A*h)/1000) \qquad (6)$$

where

A = S = Cross section (mm^2)
h = Height / length of the wire (mm)
ρ_{Cu} = Density of the copper is 8.96 g/cm^3 (MAOL 1992, 134)
m = 8.96 g/cm^3 *((1077.5mm^2*5000mm)/1000) = 5387500 mm^3 = 48.3 kg.

Weight difference would be 48.3 kg (1077.5 mm^2) versus 1.5 kg (34.5 mm^2 cable). Thinner cables are also easier to route in vehicles and handling of the cables in every work-phase is naturally easier.

Other arguments for using a higher voltage are the reduction of weight in the complete wiring system, improved stability and reduced voltage drop. With 30 times (24 V x 30 = 720 V) the voltage, thick conductors can be reduced to a 30th of the cross-section, and at the same time the relative voltage drop can also be reduced to a 30th. For the same cross-section, the relative voltage drop is now no more than 1/90.

2.6 Charging of the Power Train Energy Storage

Volvo Bus has selected parallel hybrid technique (Figure 3) to their vehicle called “Volvo 7900 Electric Hybrid”. The diesel motor is a four cylinder engine with 240 hp / 918 Nm. The maximum output power of the electric motor called (Volvo I-SAM) is 150 kW / 1200 Nm. The energy storage system is based on high capacity lithium-ion batteries with a total energy capacity of 19 kWh. This enables 7 km electric drive between charges or 70% of the route. Charging time is only 6 minutes. The bus can carry 95 passengers.

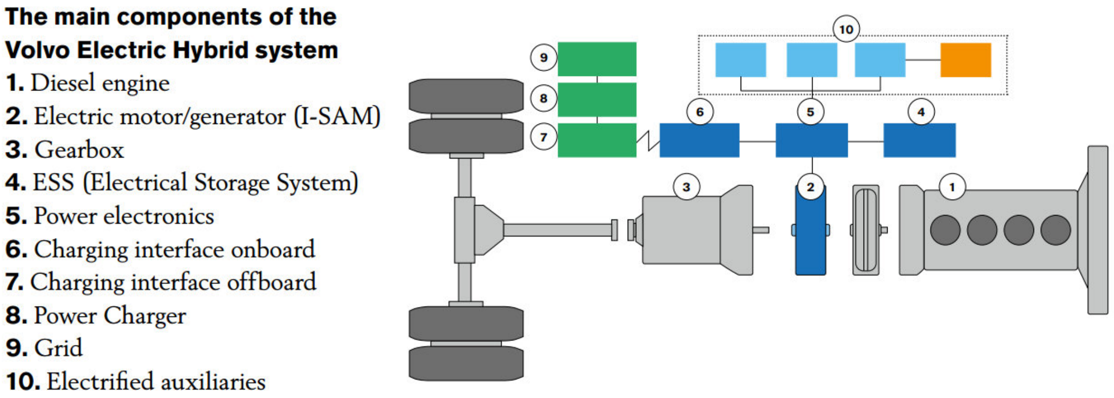


Figure 3. Main components of the Volvo Electric Hybrid System (Volvo Bus Corporation 2014b)

The charging system is designed to be part of the ordinary bus stops (Figure 4) and it includes the complete interface between the energy grid and the vehicle. Charging starts automatically when the bus stops in the right position. The charging contacts reach the bus from above, which is optimal in terms of the safety. All moving parts are integrated in the pylon, while the contacts on the bus are fixed-mount connectors. This minimizes the need for additional maintenance on the vehicle and reduces the vehicle weight, thus increasing passenger capacity. (Volvo Bus Corporation 2014c.)

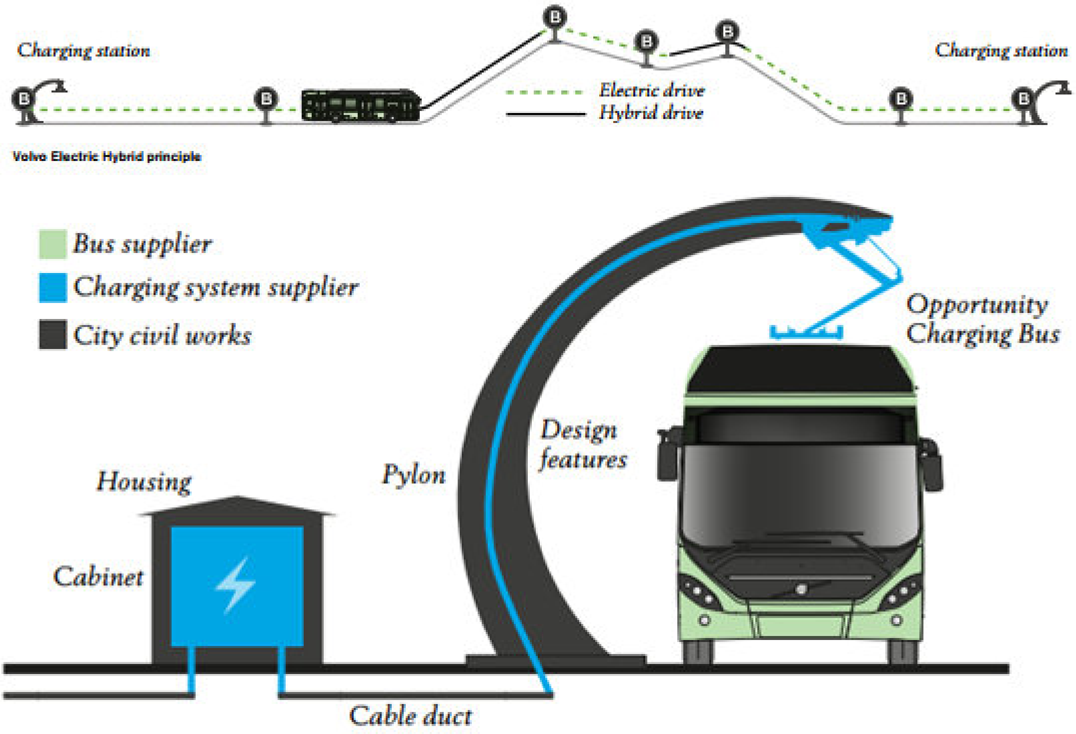
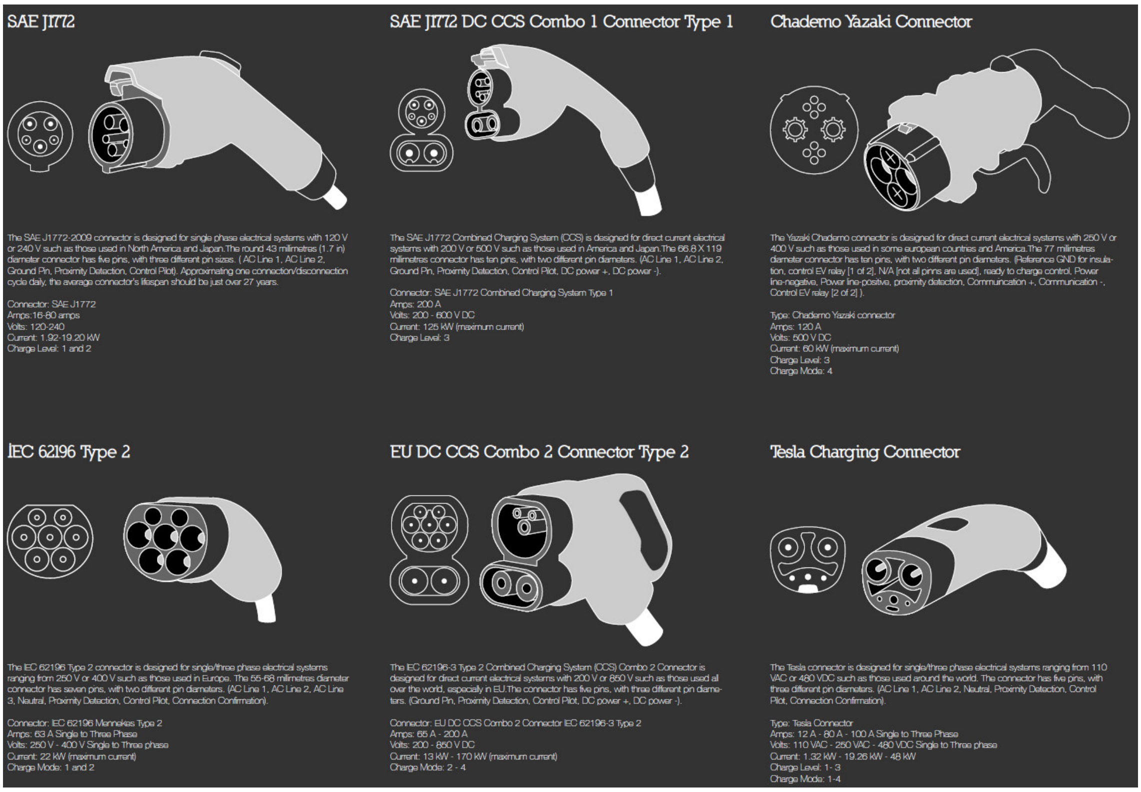


Figure 4. Volvo Opportunity Charging System can be integrated to bus stop structure (Volvo Bus Corporation 2014c)

In addition to charging system, which is integrated to part of the bus stops as shown in Figure 4, there are different kinds of the charging stations and plugs in use depending on car manufacturers. Although passenger car manufacturers are driving this development, as well as wireless charging, those can be used also with commercial vehicles depending on voltage levels. IEC 62196-1 is applicable on plugs, socket-outlets, connectors, inlets and cable assemblies for electric vehicles. It also refers to four charging modes (Mode 1 to 4) which are defined in IEC 61851-1. The different types of the charging connectors are shown in Figure 5. According to IEC 62196-1, the operating voltage in a conductive charging system cannot exceed 690 V_{AC} (50-60 Hz) / 250A and 600 V_{DC} / 400A. IEC 62196-3 represents voltage level up to 1000 V_{DC} / 400A for Mode 4.



SAE J1772

The SAE J1772-2009 connector is designed for single phase electrical systems with 120 V or 240 V such as those used in North America and Japan.The round 43 milimetres (1.7 in) diameter connector has five pins, with three different pin sizes. (AC Line 1, AC Line 2, Ground Pin, Proximity Detection, Control Pilot). Approximating one connection/disconnection cycle daily, the average connector's lifespan should be just over 27 years.

Connector: SAE J1772
Amps:16-80 amps
Volts: 120-240
Current: 1.92-19.20 kW
Charge Level: 1 and 2

SAE J1772 DC CCS Combo 1 Connector Type 1

The SAE J1772 Combined Charging System (CCS) is designed for direct current electrical systems with 200 V or 600 V such as those used in America and Japan.The 66.8 X 119 milimetres connector has ten pins, with two different pin diameters. (AC Line 1, AC Line 2, Ground Pin, Proximity Detection, Control Pilot, DC power +, DC power -).

Connector: SAE J1772 Combined Charging System Type 1
Amps: 200 A
Volts: 200 - 600 V DC
Current: 125 kW (maximum current)
Charge Level: 3

Chademo Yazaki Connector

The Yazaki Chademo connector is designed for direct current electrical systems with 250 V or 400 V such as those used in some european countries and America.The 77 millimetres diameter connector has ten pins, with two different pin diameters. (Reference GND for insulation, control EV relay [1 of 2], N/A [not all pinns are used], ready to charge control, Power line-negative, Power line-positive, proximity detection, Commuincation +, Communication -, Control EV relay [2 of 2]).

Type: Chademo Yazaki connector
Amps: 120 A
Volts: 500 V DC
Current: 60 kW (maximum current)
Charge Level: 3
Charge Mode: 4

IEC 62196 Type 2

The IEC 62196 Type 2 connector is designed for single/three phase electrical systems ranging from 250 V or 400 V such as those used in Europe. The 55-68 millimetres diameter connector has seven pins, with two different pin diameters. (AC Line 1, AC Line 2, AC Line 3, Neutral, Proximity Detection, Control Pilot, Connection Confirmation).

Connector: IEC 62196 Mennekes Type 2
Amps: 63 A Single to Three Phase
Volts: 250 V - 400 V Single to Three phase
Current: 22 kW (maximum current)
Charge Mode: 1 and 2

EU DC CCS Combo 2 Connector Type 2

The IEC 62196-3 Type 2 Combined Charging System (CCS) Combo 2 Connector is designed for direct current electrical systems with 200 V or 850 V such as those used all over the world, especialy in EU.The connector has five pins, with three different pin diameters. (Ground Pin, Proximity Detection, Control Pilot, DC power +, DC power -).

Connector: EU DC CCS Combo 2 Connector IEC 62196-3 Type 2
Amps: 65 A - 200 A
Volts: 200 - 850 V DC
Current: 13 kW - 170 kW (maximum current)
Charge Mode: 2 - 4

Tesla Charging Connector

The Tesla connector is designed for single/three phase electrical systems ranging from 110 VAC or 480 VDC such as those used around the world. The connector has five pins, with three different pin diameters. (AC Line 1, AC Line 2, Neutral, Proximity Detection, Control Pilot, Connection Confirmation).

Type: Tesla Connector
Amps: 12 A - 80 A - 100 A Single to Three Phase
Volts: 110 VAC - 250 VAC - 480 VDC Single to Three phase
Current: 1.32 kW - 19.26 kW - 48 kW
Charge Level: 1- 3
Charge Mode: 1-4

Figure 5. Different types of the charging connectors (InsideEVs 2015)

Mode 1 charging is normally used with light electric vehicles (LEV). It is a AC charging method from household socket-outlets. The supplying circuit shall be provided with a residual current device (RCD) and maximum 1 or 3 phase AC current is 16A. (Vesa 2016, 9.)

Mode 2 charging (a.k.a. slow charging) cable is equipped with an in-cable control box (IC-CPD) which includes control and safety related functionalities such as restriction of the charging current. It provides 1-, 2- or 3-phase charging with AC up to 32 A. (Vesa 2016, 9.)

Mode 3 charging (a.k.a. basic charging) is an AC supply from a dedicated EV socket-outlet or connector. There are extended safety functionalities such as “continuous protective earth conductor continuity checking” and “no proper connection - no voltage” feature. Mode 3 provides 1-, 2- or 3-phase charging with AC up to 3x63 A or 1x70 A. It can also control the charging current and feeding back electricity from V2G. (Vesa 2016, 8.)

Mode 4 charging (a.k.a. power charging) is a DC charging from an external charger with fixed charging cable in a charging station. Mode 4 enables flexible and controllable charging with a theoretically max. power 120-170 kW. The maximum current is limited to 400A (DC). (Vesa 2016, 8.)

The wireless charging transfer system, communication between EV and infrastructure and requirements for the magnetic field power transfer systems are defined in IEC/TS 61980-1 to -3. The battery swapping system description and general & safety requirements are defined in IEC 62840-1 and -2. (Vesa 2016, 10.)

2.7 Main Challenges in the HV System

In the conference “Bordnetze im Automobil” organized in Ludwigsburg 25 March 2014 Dr. Tobias Moosmayr and Andreas Heim listed the following issues to be taken into account with electrical system including high voltage:

- Shielding of the cables
- Preventing the short-circuit faults to the low voltage system
- Tighter vibration requirements for wires and connectors
- Thermal stress
- Easy assembly in the factory
- Standardization of the charge plug

Udo Hornfeck, Vice President R&D from LEONI Bordnetz-Systeme GmbH listed the following things in his presentation:

- Voltage up to 1000 V
- High safety requirements
    - Touch protection, mechanical protection
    - HV interlock loop (HVIL)
    - Separate installation routes (12 V, fuel lines)
- Distribution of two potentials PLUS / MINUS
    - Additional cables
    - Distributors with both potentials
- New components and processes
    - Standardization is not advanced
- EMC protection required
    - Screened cables
    - Screen connection and transfer
- HV lines (Powertrain)
    - Great cross-section ➔ high weight

- High cost of the materials ➔ expensive
- Some processing and laying differences

2.8 Standardization

Standardization regarding electric vehicles is under development. Safety issues and charging are being under discussion but some parts are already standardized. Vehicle manufacturers have their own standards and requirements based more or less on international standards. Those need to be taken into account during development. EMC requirements are similar to LV systems (Table 11 International Automotive Standards for Component Testing (on page 74). ISO standards, which respond to the keyword “electrically propelled vehicles” in www.ISO.org are listed in Appendix 3.

3 MAIN COMPONENTS IN AUTOMOTIVE HV SYSTEM ARCHITECTURE

This chapter introduces the components needed between the electric motor(s) and batteries such as cables, connectors, fuses, relays and electric centers. The aim is to provide basic knowledge about these electrical components and shortly list the main requirements and exemplary manufacturers. All other bigger units like electric motors, HV battery stores, DC/DC converters, regenerative braking systems etc. have been intentionally left without attention.

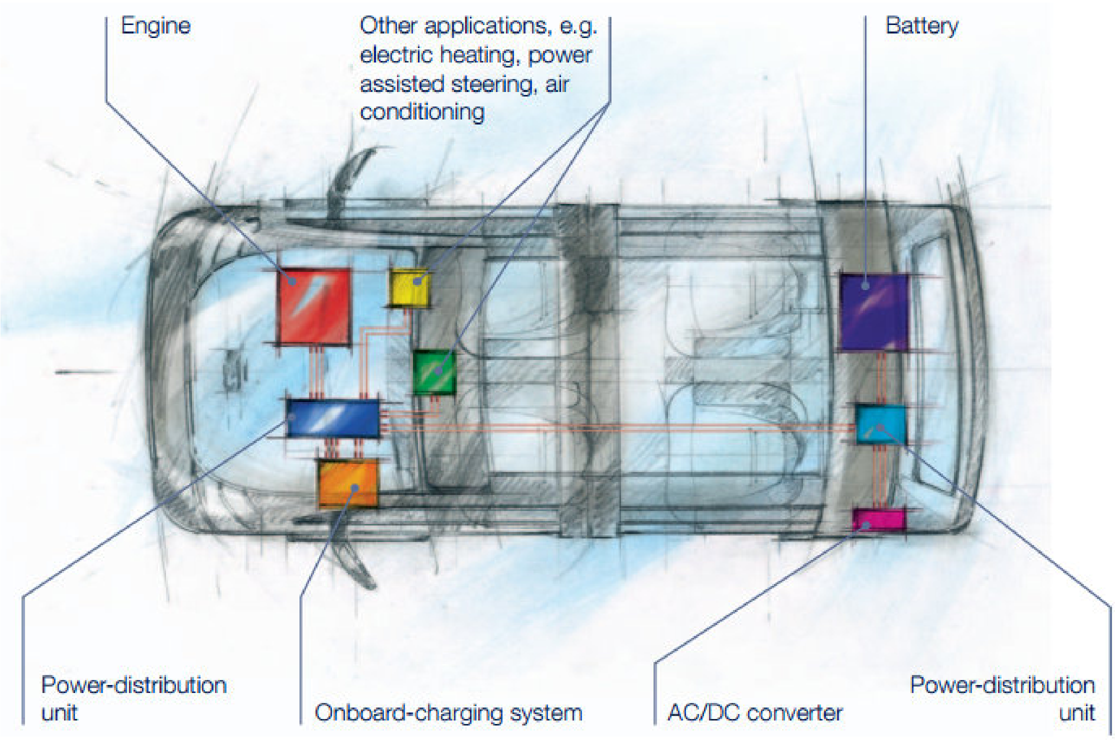
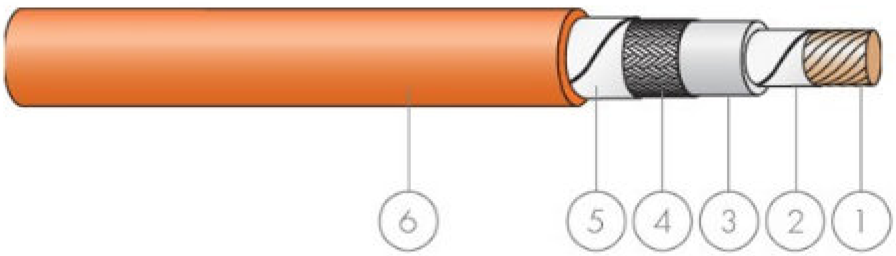


Figure 6. HV components in a power train (Rosenberger 2015)

3.1 Wires & Cables

The basic structure of the HV cable is in Figure 7. The most significant difference when compared to traditional cables is the EMC screening between the sheath and conductor. This is meant to be connected to the chassis via connectors and device bodies for preventing EMC disturbances. For safety reasons, the HV cables have to be identified on the car with an orange color. Bending radius may be gentler compared to traditional cables.

Number of conductors	1
Cross section	1.5 to 150 mm²
Voltage rating	600 / 1000 V AC
Temperature range	-55 to +150 °C (3000 h)
Min. bending radius	4 x cable dia.



Composition of cable

1	Conductor	stranded bare copper
2	Tape	plastic
3	Insulation	RADOX®155S for 1.5, 2.5, 4.0, 6.0 mm²; RADOX® 155 for > 6 mm²
4	EMC screen	tin plated copper braid optimised
5	Tape	plastic or aluminium screen (optional)
6	Sheath	RADOX® Elastomer S, colour: orange

Figure 7. Structure of the RADOX® high voltage cable (Huber+Suhner 2014)

Some leading exemplary manufacturers of the HV cables are Huber+Suhner, Leoni and General Cable

3.2 Connectors & Housings

The color of the HV connectors is not defined, which is convenient from the installation point-of-view. Different colors as well as mechanical key coding help to prevent connection mistakes during the assembly of the wiring harness to actuators. The biggest differences compared to LV connectors are 360° EMC shielding around connection points and higher walls around connection points for preventing accidental touching of a live part. IP sealing is implemented more or less as in LV systems, but structure of the HV cable requires accuracy in the assembly phase. HVIL requirement adds a pair of the signal wires inside the housing.

One example of the high voltage connector manufacturer is Molex. Imperium™ High-Voltage/High-Current (HVHC) connector system (Figure 8) meets commercial vehicle requirements. The connectors are capable of handling up to 1000V and 250A per contact.

Figure 8. Molex Imperium™ High-Voltage / High-Current (HVHC) connector system (Molex 2017)

Exploded view of the wiring harness connector is shown on Figure 9. The structure is quite similar regardless of the manufacturer.

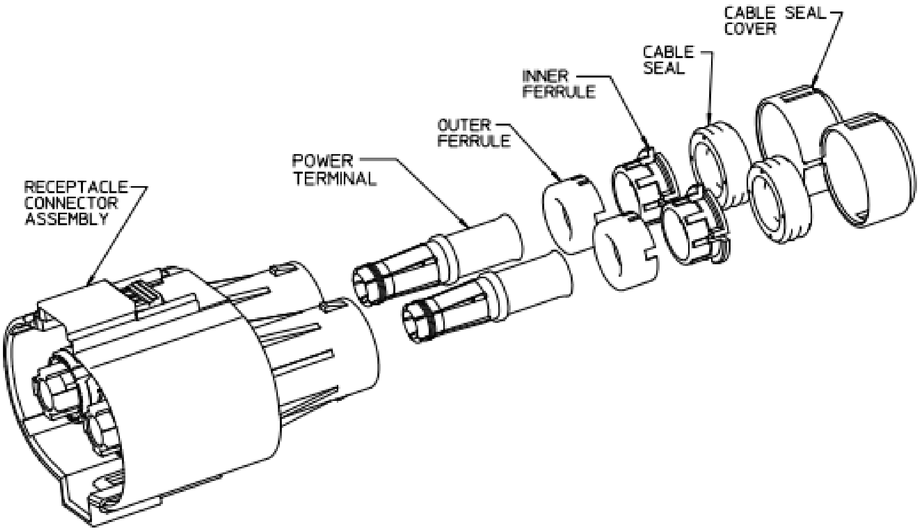


Figure 9. Exploded view of the Molex Imperium™ High-Voltage / High-Current (HVHC) connector system (Molex 2013)

Other well-known HV connector manufacturers are Rosenberger, Hirschmann Automotive, Tyco Electronics, Amphenol and Yazaki.

3.3 Fuses

Basic fuse operation is simple: excess current passes through specially designed fuse elements causing them to melt and open, thus isolating the overloaded or faulted circuit. Fuses now exist for many applications with current ratings of only a few milliamps to many thousands of amps and for use in the circuits of a few volts to 72 kV utility distribution systems. The most common use for fuses is in electrical distribution systems where they are placed throughout the system to protect cables, transformers, switches, control gear and equipment. Along with different current and voltage ratings, fuse operating characteristics are varied to meet specific application areas and unique protection requirements.

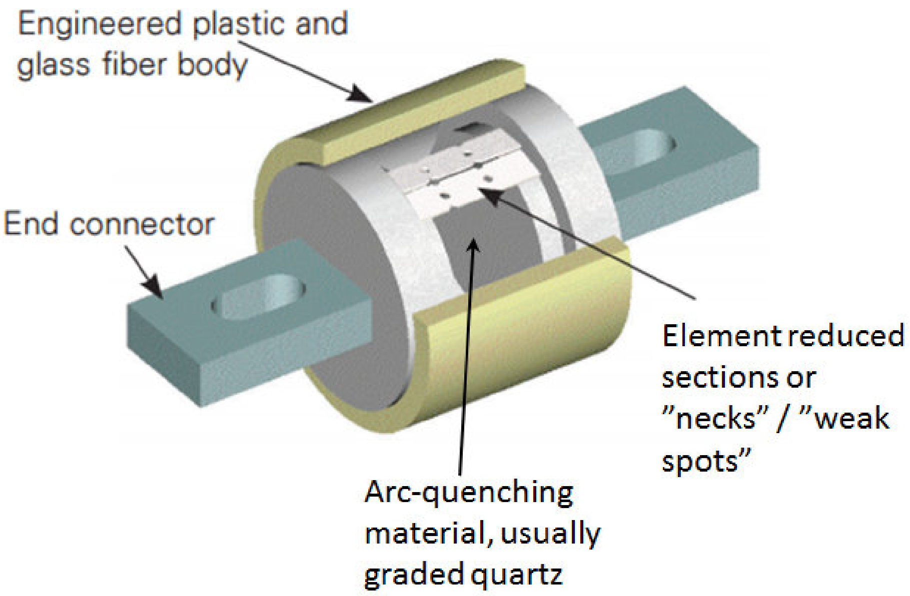


Figure 10. Typical construction of a high voltage fuse (Eaton 2016)

Although all fuse components influence the total fuse operation and performance characteristics, the key part is the fuse element. This is made from a high conductivity material and is designed with a number of reduced sections commonly referred to as “necks” or “weak spots.” These reduced sections mainly control the fuse’s operating characteristics. The element is surrounded with an arc-quenching material, usually graded quartz, which “quenches” the arc that forms when the reduced sections melt and “burn back” to open the circuit. This gives the fuse its current-limiting ability. To contain the quartz arc-quenching material, an insulated container (fuse body) is made of ceramic or engineered plastic. Finally, to connect the fuse element to the circuit it protects there end connectors, usually made of copper. (Eaton 2016.)

Fuse operation depends primarily on the balance between the rate of heat generated within the element and the rate of heat dissipated to external connections and surrounding atmosphere. For current values up to the fuse’s continuous current rating, its design ensures that all the heat generated is dissipated without exceeding the pre-set maximum temperatures of the element or other components. (Eaton 2016.)

The time taken from the initiation of the short circuit to the element melting is called the pre-arcing time. This interruption of higher current results in an arc being formed at each reduced section with the arc offering a higher resistance. The heat of the arcs vaporizes the element material; the vapor combines with the quartz filler material to form a nonconductive. The arcs also burn the element away from the reduced sections to increase the arc length and further increase the arc resistance.

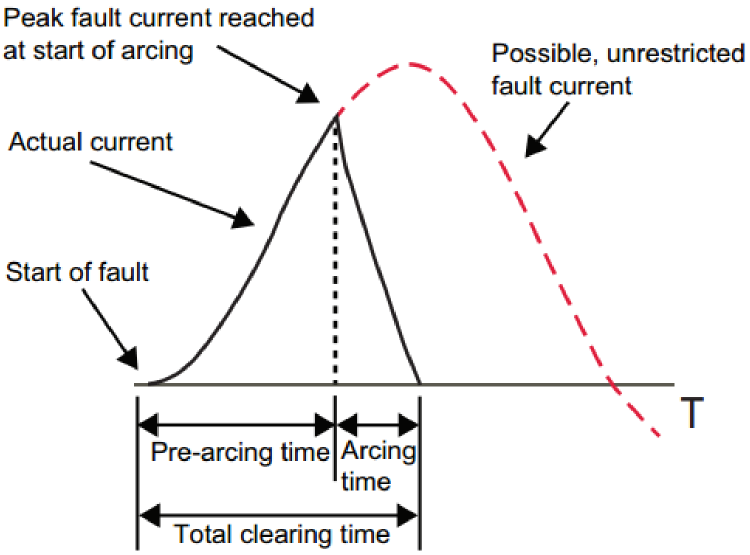


Figure 11. Pre-arcing time plus arcing time equals total clearing time (Eaton 2016)

Arcing causes a voltage across the fuse element that reduced sections (necks) and is termed the arc voltage (Figure 12). This arc voltage will exceed the system voltage. The design of the element allows the magnitude of the arc voltage to be controlled to known limits. The use of a number of reduced sections (necks) in the element, in series, assists in controlling the arcing process and also the resulting arc voltage. Thus, a well-designed fuse not only limits the peak fault current level, but also ensures the fault is cleared in an extremely short time and the energy reaching the protected equipment is considerably smaller than what is available. (Eaton 2016.)

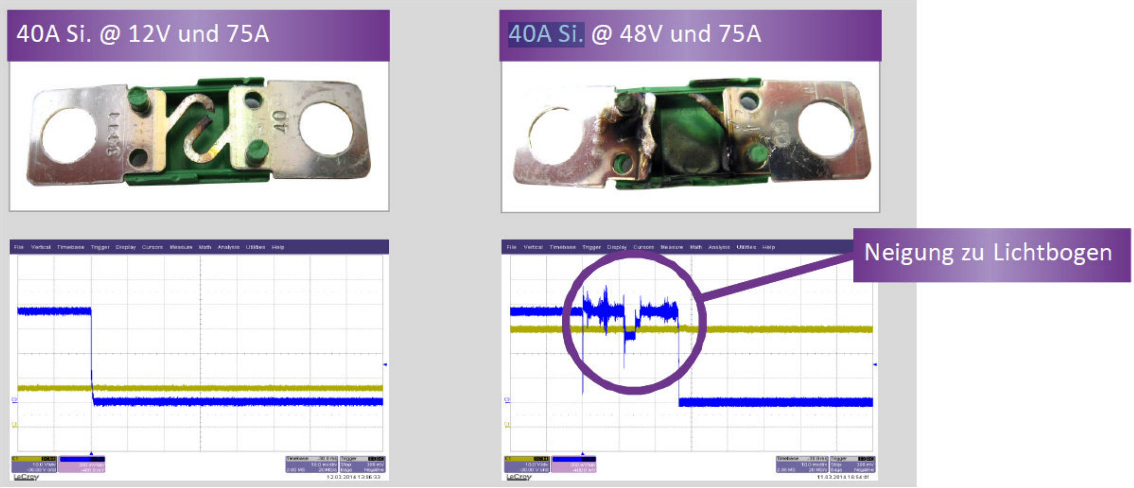


Figure 12. Arcing when fuse blows in 48V system (Kromberg & Schubert 2014)

During an overload situation, the rate of heat generated is greater than that dissipated, causing the fuse element temperature to rise. The temperature rise at the reduced sections of the elements (“necks” or “weak spots”) will be higher than elsewhere, and once the temperature reaches the element material melting point it will start arcing and “burn back” until the circuit is opened. The time it takes for the element to melt and open decreases with increasing current levels. (Eaton 2016.)

Eaton’s Bussmann® series EV fuses provides 500 $V_{AC/DC}$ compact high speed fuses from 50 A to 400 A. Fuses are equipped with either ferrule, bolt-on or PCB terminals. They are also able to offer fuses rated over 1000 V_{DC} and 1000A. These fuses can be designed to meet unique requirements including shock and vibration, mounting requirements, high temperature performance or other parameters.

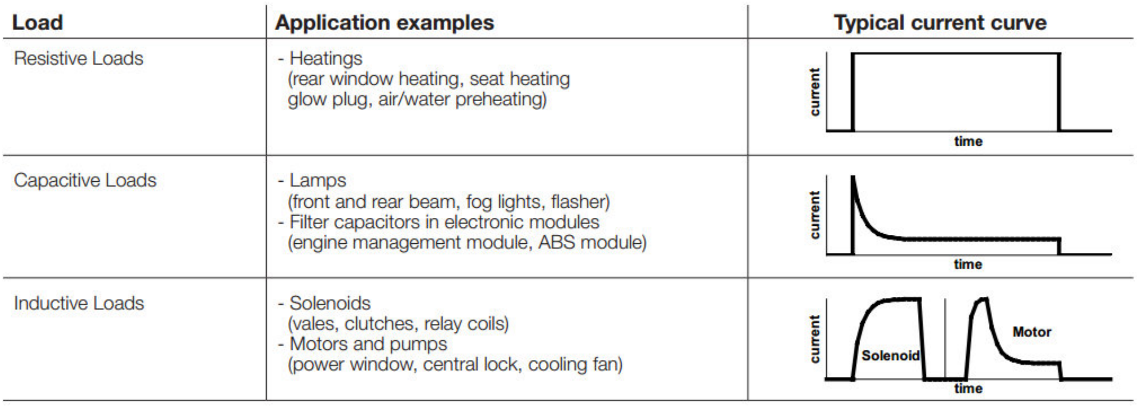
Figure 13. Bussmann series compact high speed fuses from Eaton (Eaton 2017)

Other well-known HV fuse manufacturers are Littelfuse and PEC.

3.4 Relays

Relay (also called as contactor) manufacturers provide switching solutions for automotive HV environment but there are several variations between implementation, current handling capacities and physical sizes.

In automotive applications, relays should be able to connect and disconnect typically three different kind of loads: resistive, capacitive and inductive (Figure 14). Load voltage and load resistance specifies the current curve of resistive loads. Capacitive loads have a high inrush current and a low steady current. Therefore, lamps are counted to the capacitive loads, because the cold filament has a significantly lower resistance, than the hot filament. Inductive loads are characterized by an exponential current increase and a remarkable switch off arc, induced by the demagnetization of the magnetic circuit of the load. Power supply relays (clamp relays) can switch or feed a mixture of the different loads. (TE Connectivity 2015.)



Load	Application examples	Typical current curve
Resistive Loads	- Heatings (rear window heating, seat heating glow plug, air/water preheating)	
Capacitive Loads	- Lamps (front and rear beam, fog lights, flasher) - Filter capacitors in electronic modules (engine management module, ABS module)	
Inductive Loads	- Solenoids (vales, clutches, relay coils) - Motors and pumps (power window, central lock, cooling fan)	

Figure 14. Typical loads in automotive applications (TE Connectivity 2015)

The main contactor is used for separating the energy storage from the vehicle electrical system. The purpose is presented widely in chapter 4.5.1 Main Contactors.

The requirements for the main contactor under normal operation conditions are:

- Connect and disconnect the battery from rest of HV system
- Carry several hundred Amps with low power dissipation
- Ensure full galvanic isolation, when the vehicle is turned off. (TE Connectivity 2017.)

The requirements for failure cases are:

- The contactor must be able to switch off overcurrent of up to 2,000A
- The contactor must still be capable of separating the circuit after an overload
- The contacts must remain closed in case of overload (especially at short circuits), as long as the contactor is activated. (TE Connectivity 2017.)

Gigavac is one supplier who provides contactors for high voltage environment. Contactors can switch loads from 12 to 1500 V_{DC} up to 1000 Amp. Coil voltage can be selected to be 12, 24 either 48 V_{DC}. As an example Gigavac GX110 contactor (Figure 15) is able to connect 1000A current continuously and even 5000A during 10s over voltage range 12 – 800 V_{DC}. The operating temperature of this relay is -55 ℃ to +85 ℃ and the physical size is (LxWxH): 142.6 x 135.6 x 76.2 mm and weight 1.6 kg. (Gigavac 2016.)

Figure 15. Gigavac GX110 contactor (Gigavac 2016)

Other known manufacturers are ETA, Hongfa, Amphenol, Tyco Electronics and Kissling.

3.5 HV Power Distribution Units

The power distribution unit is a junction point and centralized location for main fuses for protecting the wires and actuators in the automotive electrical system. For reaching the electrical demands, robustness, human safety, IP and EMC requirements the high voltage distribution units need to be covered by a metal shield. Because of the low production volumes a standard stainless steel or aluminum boxes are usually used at the time when this thesis was written. In the future when the quantities are higher, also casings will be more customized as Figure 19. Two different outlook of the PDU (Leoni) shows. Usually OEMs have their own demands regarding connectors and devices inside the box as well directions where cables need to point out etc. That is why it is seldom possible to design and provide ready-made off-the-shelf products. In those cases, compromises cannot be avoided.

As mentioned, in low annual quantity products, standard enclosures are usual the only possible solution from the economic point-of-view. Rolec Gehäuse-Systeme GmbH provides stainless steel (A2 / A4) inoCASE enclosure family. IP class 67 is possible to be reached with a silicone gasket.

Space-saving single-channel lid and assembly fastening, outside the enclosure interior.

Silicone gasket glued into the lid, stamped.

Fastening lugs in the enclosure bottom for components.

Figure 16. Some Rolec inoCASE features (Rolec)

Standard sizes variates from (LxWxH) 100x70x50 mm (inoCASEmini A2/A4) to 430x300x120 mm (inoCASE A2/A4). Customer-specific forms, versions and dimension are naturally available. It is also possible to order casings with laser markings, engraving or with different printings either special coating. (Rolec.)

Inside of the metallic enclosure a “fixation basement” for cable terminals, busbars, fuses and all other peripherals is needed. In low-volume products, milled plastic part is a reasonable choice. It acts at the same as an insulator between outer enclosure and components.

Bender GmbH & Co. KG provides Hybrid Vehicle Distribution Box with an integrated insulation-monitoring device (IMD) for unearthed DC drive systems in electric vehicles. Voltage range is 0 - 750 V_{DC}. Maximum dimension of the stainless steel casing is (LxWxH) 420 x 330 x 96 mm including fixation points. Weight is 9 kg without fuses and IP class is 69K. Ambient temperature is - 40 to + 70 °C. (Bender 2016).

Figure 17. Hybrid Vehicle Distribution box (Bender 2016)

It consists mainly of an ISOMETER® IR155-3204 IMD and space to accommodate a maximum of six Siemens series 3NE8720-1 fuses. 3NE87xx series includes fuses from 20A to 315A, but in this application the fuse size is limited to 80A.
(Siemens 2016)

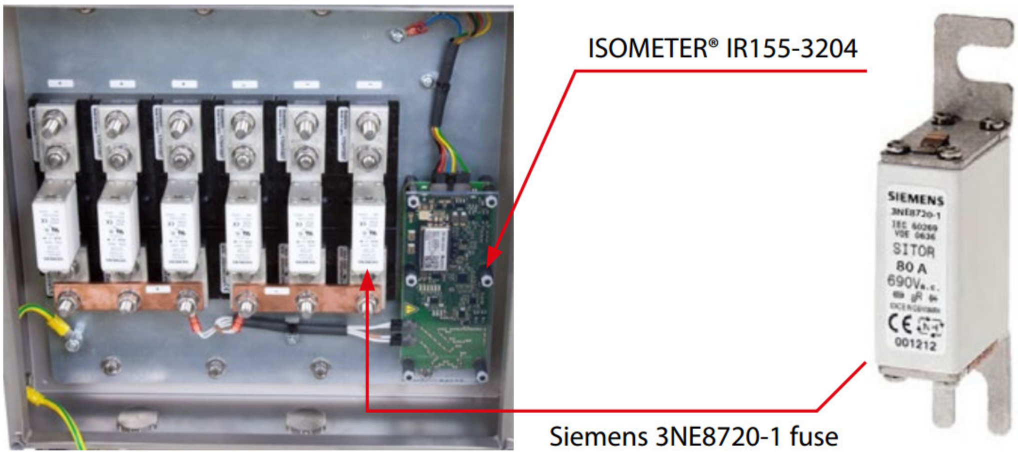


Figure 18. Inside of the Hybrid Vehicle Distribution box (Bender 2016)

According to the fuse datasheet its maximum allowed ambient temperature is -20 to + 50 °C and its rated only up to 700 V_{DC}. Overall, Bender datasheet asserts that Siemens AG has verified the suitability of these fuses for this application.
Purpose of the IMD is to monitor continuously insulation resistance, detect earth faults and under-voltage (<100 V) situations. (Bender 2016)

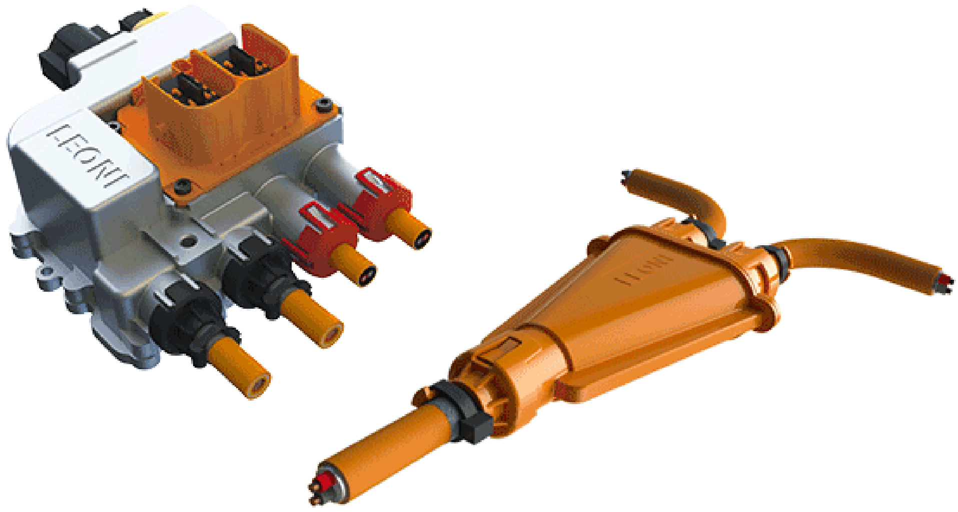


Figure 19. Two different outlook of the PDU (Leoni)

A typical unit can distribute power to several HV components (e.g. from 5 A to 300 A and up to 800V_{DC}) and can also include safety and security devices. Key features can include shielded single and multi-core interconnections with a low contact resistance for EMC shielding and high power connections. One example about this kind of PDU shown on left side of Figure 19. (Leoni)

One example of Leoni’s HV components is the Y-Power distribution (or splitter) unit (Right side on Figure 19). With one input and two output lines, the Y-Power distribution unit provides a more direct transfer of power to the auxiliary units in hybrid and electric vehicles. It is small, lightweight and cost effective. The Y-Power distribution unit also provides an efficient method of extending the capability of the high-voltage network. (Leoni)

4 HUMAN SAFETY IN HV VEHICLES AND PRODUCTION

The prevention of health risks among people involved in the development, manufacturing, maintenance or use of the products for the high voltage range has a top priority. Potential risks are electric energy, accidental arcs, electric current flowing through the body (electric shock), electromagnetic fields affecting e.g. pacemakers and interactions between electric energy and other media. (ZVEI 2013.)

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. (ZVEI 2013.)

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. (ZVEI 2013.)

Thermal effect

The current flow causes burns on the entry and exit points and coagulation of protein in the body. (ZVEI 2013.)

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 high voltage. Safeguards must be put in place to prevent the potential risks associated with HV and the resulting damage to humans and animals. (ZVEI 2013.)

4.1 Why is High Voltage Dangerous?

High voltage itself will not kill, but current does. In practice, the electric shock (I) requires: Voltage source (U), resistance (R) and a closed circuit. Figure 20 presents how different current levels affect human body. That describes why residual current circuit breakers are adapted to maximum for 30 mA currents.

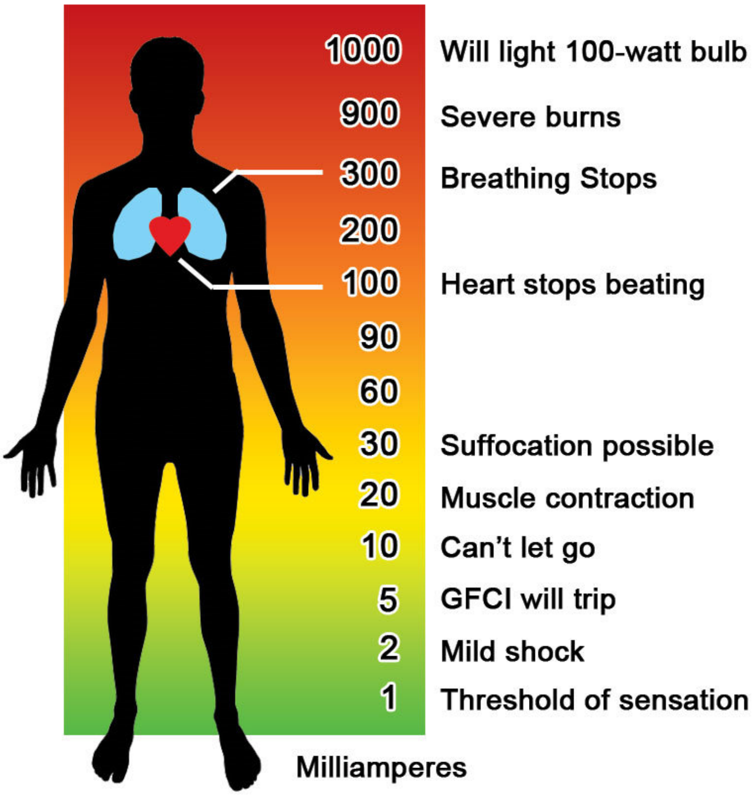
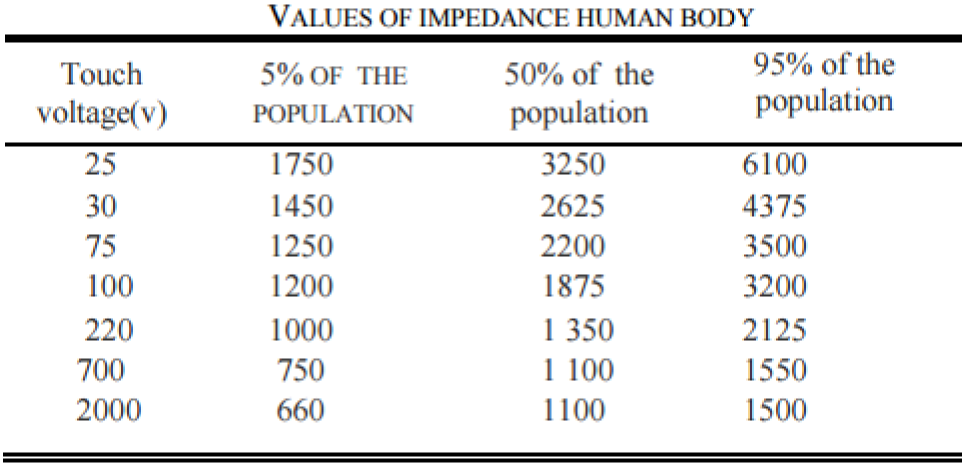


Figure 20. How AC current affects the body (testguy.net)

The resistance of human skin varies from person to person and fluctuates between different times of day. The averaged resistances of human body are shown in Table 2. The current path influences the value of the impedance of the human body. E.g. the impedance from a current path one hand to both feet is 75 %, and the impedance from both hands to both feet 50 % , and from both hands to the trunk of the body 25 % of the impedance hand-hand (100 %). As far as the effect of frequency is concerned, the impedance of the skin decreases when the frequency increases. (Quazani & Habi 2013)

Table 2 Human body resistance (Ω) with different voltages (Quazani & Habi 2013)



VALUES OF IMPEDANCE HUMAN BODY

Touch voltage(v)	5% OF THE POPULATION	50% of the population	95% of the population
25	1750	3250	6100
30	1450	2625	4375
75	1250	2200	3500
100	1200	1875	3200
220	1000	1 350	2125
700	750	1 100	1550
2000	660	1100	1500

According to Table 1 if voltage is under 50 V_{AC} risk for electric shock is low. Estimating from Table 2 the lowest impedance with that voltage is 1350Ω. Keeping it simple we can calculate current by Ohm's Law (I=U/R). I= 50 V_{AC} / 1350 Ω = 37 mA which means that in some cases there is risk for suffocation and muscle contraction but human should to survive alive in any cases.

According to Electronics Handbook, the effects of alternating current shock are more dangerous than the direct current shock at the same current levels (rms and DC). The sensation level for DC is about 5 mA, as opposed to 1 mA (rms) for AC at 60 Hz. The let-go threshold for AC at 60 Hz is 10–20 mA (15 mA average). For DC, the let-go threshold is on the order of 75 mA, a figure that is higher than the corresponding maximum peak-to-peak AC value at the 20 mA rms level. When there is a direct current path through the heart, a momentary alternating current of 60 mA (rms) at 60 Hz can induce ventricular fibrillation (defined subsequently), whereas a direct current in the range from 300 to 500 mA is required. (Ferris C. D 2005)

Table 1 also refers that there is a low electric shock risk if the voltage is under 120 V_{DC}. Calculating current with the same impedance as earlier (1350 Ω) I = 120 V_{DC} / 1350 Ω = 89 mA. This is on the line of the fact that DC can be 2-4 times higher than AC. The estimated resistance of human body variates depending on the sources. A couple of examples are given in Figure 21.

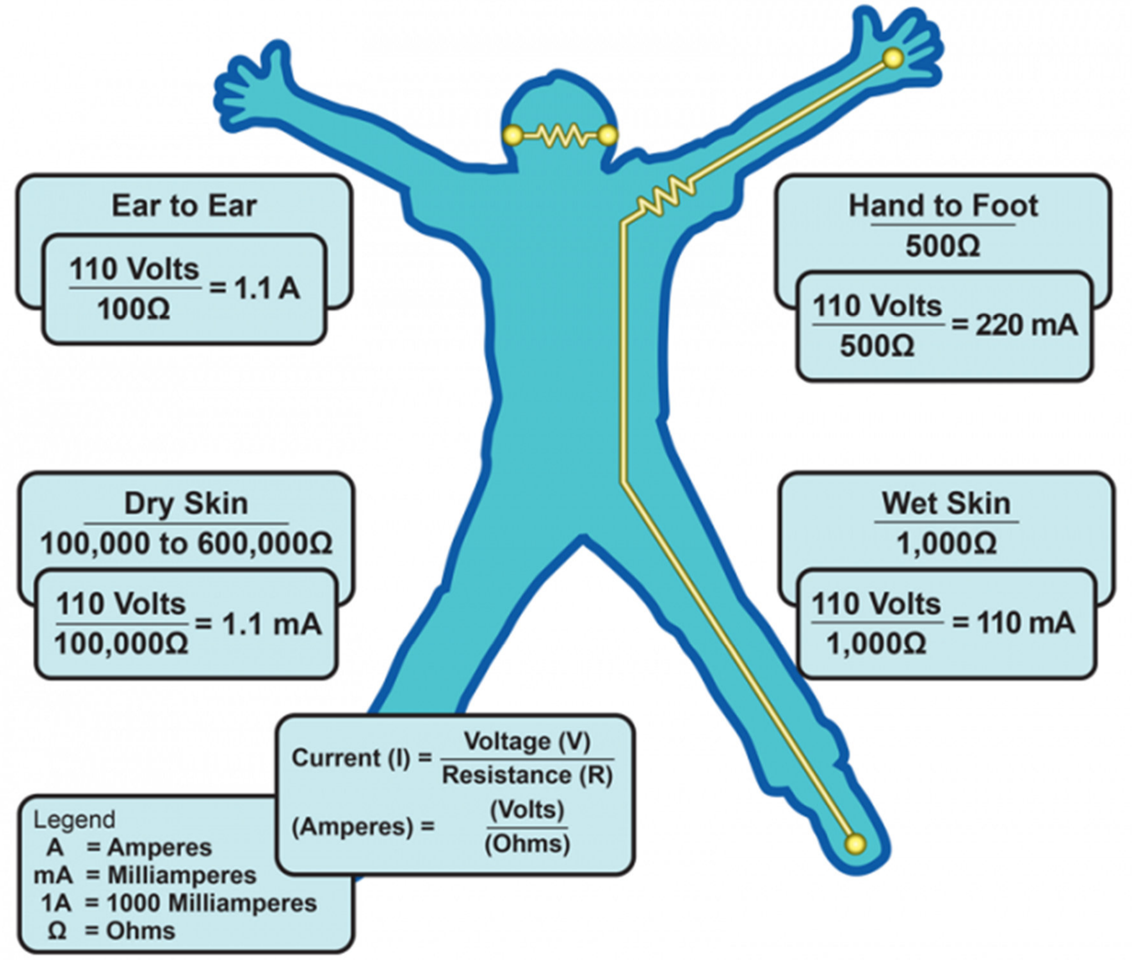


Figure 21. Typical body resistances and current flows (Technology Transfer 2014)

4.2 Electric Safety in the Company Facilities

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_{DC}, 24 V_{DC}, 42 V_{DC} automotive products) must adapt their safety requirements to meet high-voltage conditions. (ZVEI 2013.)

To ensure the appropriate level of the protection, it is necessary to observe following standards:

- EN 50110-1 Operation of electrical installations. General requirements
- EN 50110-2 Operation of electrical installations. National annexes

Most important is 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 as shown in Figure 22.

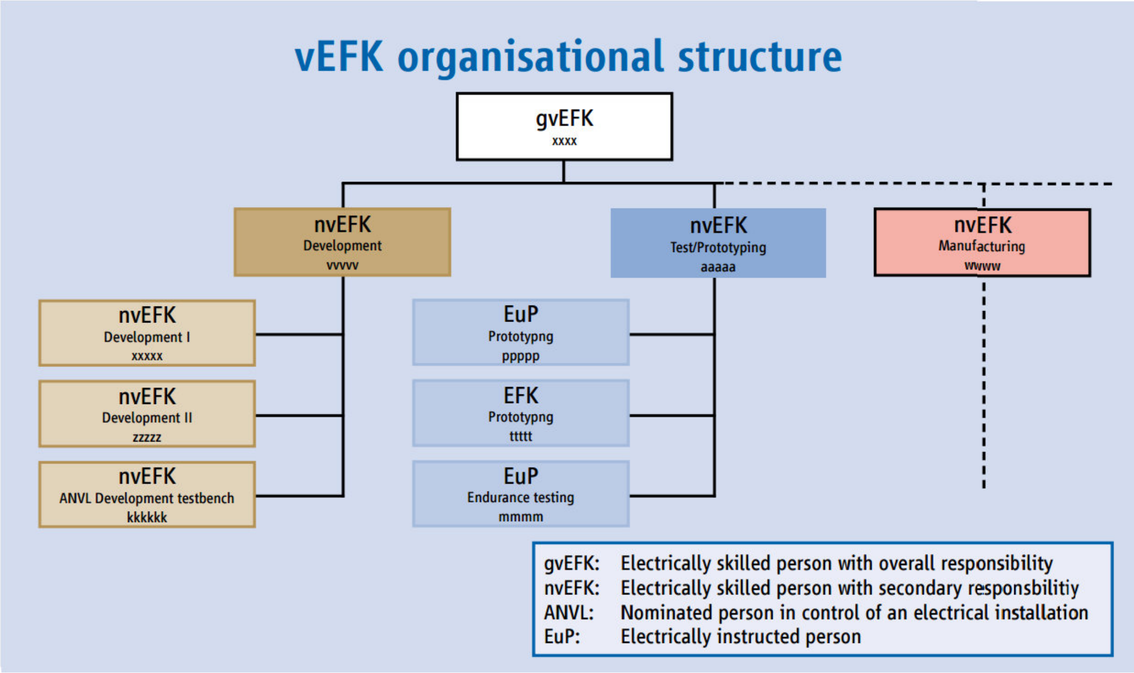


Figure 22. Organizational structure of the electrically skilled persons – responsibilities and skills (ZVEI 2013)

By complying with these rules, employers meet their occupational health and safety obligation, which creates legal certainty for the companies. (ZVEI 2013.)

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 based on these assessments, often resulting in the alteration, conversion or extension of the laboratory and workshop stations or workplaces to ensure compliance with electrical safety requirements. Further measures that can be taken to increase electrical safety include special marking of the high-voltage workplaces and access restrictions for unauthorized personnel, as well as routine training for the employees. (ZVEI 2013.)

4.3 HV Insulation and Safety

The insulating material shall be suitable to the environmental influences and the maximum working voltage and temperature ratings of the EV and its systems.
It must be ensured that a single point of failure of the (hybrid) electric system cannot cause an electric shock hazardous to the life of any person. It must also be ensured that the components used cannot cause injury under any circumstances or conditions (rain, etc.), whether during normal operation or in unforeseeable cases of malfunction. (DAF 2012.)

The voltages of HV circuits shall be equal or less than 30 V_{AC} or 60 V_{DC} within 5 s after the vehicle is shut down. When the voltages are exceeding the specified limits, the criterion of less than 0.2 Joules for the energy in the Y-capacitors may be used instead of the voltage criterion (ISO 6469-4).

Protection against direct contact shall be provided by basic insulation of the live parts and/or barriers / enclosures which preventing access to the live parts and/or insulation, which can only be removed by the use of the tools. The barriers/enclosures may be electrically conductive or non-conductive (ISO 6469-3).

4.3.1 Isolation Surveillance Between Chassis and HV Power Circuit

An isolation surveillance system must be used to monitor the status of the isolation barrier between the HV system(s) and the chassis. The system must measure the DC insulation resistance R_{iso} between the conductive parts of the chassis and the entire conductively connected HV circuit. The minimum insulation resistance R_{iso} shall be at least 100 Ω/V for DC circuits and at least 500 Ω/V for AC circuits (ISO 6469-3). The reference shall be the maximum working voltage. The measurement procedure given in ISO 6469-1 must be used to check and calibrate the on-board isolation surveillance system. Tests must be carried out to validate and quantify the insulation resistance of the vehicle in wet conditions.

The isolation resistance R_{iso} of the entire conductively connected HV system referred to the electric chassis and R_{iso} of the Rechargeable Energy Storage when disconnected from the HV power circuit needs to be measured separately. (DAF 2012.)

4.3.2 Protection Against Electrical Shock

Generally, exposed conductive parts of voltage class B electric equipment, including exposed conductive barriers/enclosures, shall be bonded to the electric chassis for potential equalization according to the following requirements:

- All components forming the potential equalization current path (conductors, connections) shall withstand the maximum current in a single failure situation.
- The resistance of the potential equalization path between any two exposed conductive parts of the voltage class B electric circuit, which can be touched simultaneously by a person, shall not exceed 0.1 Ω. (ISO 6469-3.)

No part of the chassis or body should be used as a current return path except for fault currents. An electronic monitoring system must continuously check the voltage level between Chassis Ground and HV power circuit ground. If the monitoring system detects a DC or an AC voltage with a voltage level of more than 60 V_{DC} or 30 V_{AC}, at a frequency below 300 kHz the monitoring circuit must respond (within less than 50 ms). To mitigate the failure mode where a high voltage is AC coupled onto the vehicle's low voltage system it is mandatory that all major conductive parts of the body are equipotential bonded to the vehicle chassis with wires or conductive parts of an appropriate dimension.

Grounding is required for any component to which a wire, cable or harness connects or passes in close proximity and which is able to conduct current by the means of a single point of an insulation failure. Any components that require equipotential grounding will be connected to the main chassis ground point with a resistance to prevent a dangerous touch voltage (30 V_{AC}) given an AC coupling fault at a certain level of the parasitic capacitance. (DAF 2012.)

4.3.3 Grounding of the HV Components

For protection against electrical shock which could arise from indirect contact, the exposed conductive parts, such as the conductive barrier and enclosure, shall be electrically connected securely to the chassis by connection with an electrical wire, ground cable, by welding or by connection using bolts etc. so that no dangerous potentials are produced. The resistance between all exposed conductive parts and the electrical chassis shall be lower than 0.1 Ω when there is current flow of at least 0.2 A. This requirement is satisfied if the galvanic connection has been established by welding.

In the case of EV, which is intended to be connected to the grounded external electric power supply through the conductive connection, a device to enable the galvanic connection of the electrical chassis to the earth ground shall be provided. The device should enable the connection to the earth ground before the exterior voltage is applied to the EV and retain the connection until after the exterior voltage is removed from the vehicle. Each HV component must have a ground strap that is directly connected to the vehicle chassis ground point. This strap must be at least of 25 mm^2 and be as short as possible. (UNECE 2013)

4.4 Safety Requirements for WH and Connectors

The electrical cables and electrical equipment must be protected against any risk of the mechanical damage (stones, corrosion, mechanical failure, etc.) as well as any risk of fire and electrical shock. The color of this outer layer must be orange. The voltage class B components and wiring shall comply with the applicable sections of IEC 60664-1 on clearances, creeping distances and solid insulation; or meet the withstand voltage capability according to the withstand voltage test given in ISO 6469-3. A plug must physically only be able to mate with the correct socket of any sockets within reach. (DAF 2012.)

4.4.1 Insulation Strength of the Cables

All electrically live parts must be protected against accidental contact. The insulating material not having sufficient mechanical resistance, i.e. paint coating, enamel, oxides, fiber coatings (impregnated or not) or insulating tapes, are not allowed.

Each electrical cable must be rated for the respective circuit current and must be insulated adequately. All electrical cables must be protected from overcurrent faults according to the capacity of the individual conductors. (DAF 2012.)

4.4.2 HV Connectors

HV power circuit connectors must not have live contacts on either the plug or the receptacle unless they are correctly mated. An automatic system must detect (HVIL) if a HV power circuit connector is de-mated, for example with shorter alarm contacts within the same connector, and inhibit/remove High Voltage from both the plug and the receptacle. It is not permitted to have live terminals protected only by a removable connector cap. (DAF 2012.)

4.4.3 LV Connectors on HV components

The voltage of the live parts must become equal or below 60 V_{DC} / 30 V_{AC} within one second after the connector is separated. Each LV connector of the HV component must have a 2-pin alarm contact loop to indicate that the connector is securely connected. All loops are connected in series and if the loop is interrupted (because a LV connector has been de-mated), the HV system must automatically be switched off within 1 second. (DAF 2012.)

4.5 HV Specific Safety Components

High voltage in vehicle requires additional safety components and functions to ensure human safety. Main contactors isolate energy storage from other actuators in the vehicle. The HVIL circuit ensures that all connectors are connected properly before the HV system can start-up.

4.5.1 Main Contactors

In the case of overcurrent, the energy storage and / or HV battery must be capable of being separated from the DC HV circuit via suitable contactors, independent of the direction of the current flow. When the vehicle is turned off, the energy storage must be separated from the vehicle electrical system. Both poles of the battery should be disconnected from the vehicle electrical system (SAE J1766).

The main contactors must not open without request and those must open when the activation signal is turned off (SAE J2344). The fuse and main contactor must securely separate the battery system from the motor in case of over currents, e.g. in the event of a crash (SAE J2289). Contactors must keep full functionality, i.e. carry or separate the overcurrent, as long as the fuse has not tripped. Correspondingly, open contactors must ensure a sufficient insulation resistance between the energy storage system and the vehicle after a switch-off under fault conditions.

The architecture associated with these requirements is represented in the Figure 23.

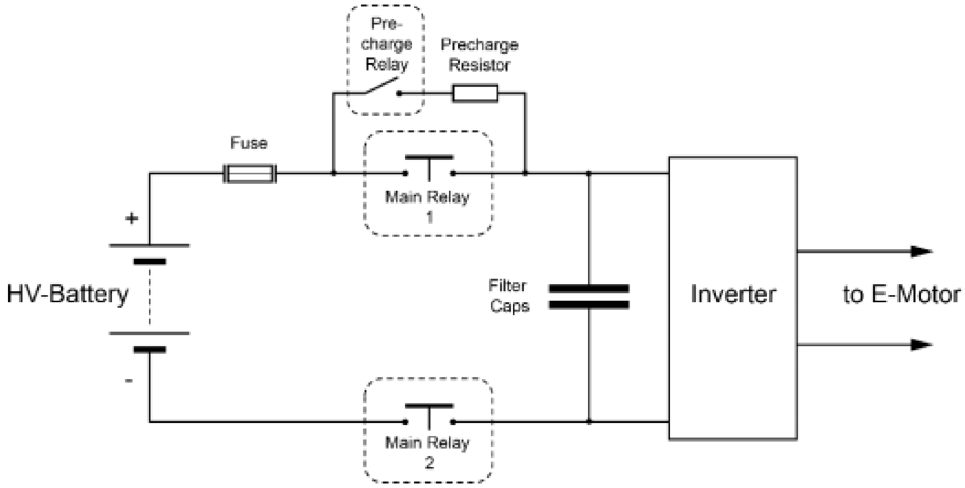


Figure 23. Schematic of the connection between the battery and the electrical system (TE Connectivity 2014, 3)

There are two main contactors, one interrupting the negative pole and the other interrupting the positive pole of the battery. In the positive path, a serial fuse is inserted. At the inverter input, filter capacitors exist, that generate a severe inrush current when the circuit is closed. This inrush current is only limited by the cable resistance and the source impedance of the battery. The effective resistance lies in the range of around 100 mΩ. In order to reduce the load to the components when switching into this capacitive short circuit, the capacitance is pre-charged before closing the main contactor via a pre-charge circuit. With a pre-charge level of 95%, a 450 V battery system will generate an inrush current limited to approximately 230 A. This current must be switched on with the main contactor at each vehicle start. (TE Connectivity 2014, 3)

4.5.2 High Voltage Interlock Loop (HVIL)

The purpose of High Voltage Interlock Loop is to protect against unintended access to a high-voltage component (e.g. an AC motor, a power inverter or the rechargeable battery pack). Specially, if HVIL switch experiences any change in electrical characteristics and indicates potential access to the HV component (e.g., an open circuit condition) the HV power supply needs to be disconnected from the HV component. (US9327601 B2 2016). HVIL also helps to eliminate HV arcing during disconnect.

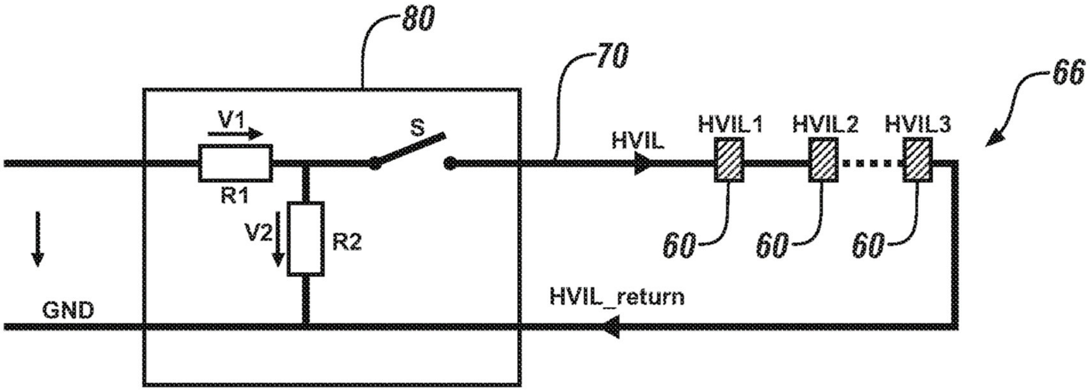


Figure 24. Basic idea of the HVIL system (US9327601 B2 2016)

In the vehicle, HVIL consists of one or more low-voltage loops in series and control module, which monitors the state of HVIL. The basic principle is introduced in Figure 24.

As an example, Molex provides Imperium™ High Voltage / High Current (HVHC) Connector system. It has an independent connector between HV contacts circulated with dashed blue in Figure 25. In the supply (male) connector there is only two pins which are internally short circuited. In the other end (female connector), there are separate pins with thin wires which can connected to part of the HVIL system.

Figure 25. Molex HVHC connector system has separate HVIL connector (Molex 2012)

One other useful solution is described in patent US9327601 B2 called: "High-voltage interlock loop (HVIL) switch having a reed relay": "In order to gain access to the HV component during the service, the housing will need to be opened. Opening the housing may make the electromechanical contacts susceptible to dirt, corrosion, or pollutants. Moreover, the electromechanical contacts may also be susceptible to tampering. Accordingly, it is desirable to provide an HVIL switch that has increased durability and reliability, and has also an increased resistance to tampering. (US9327601 B2 2016.)

A high-voltage system for a vehicle includes a HV source providing HV power, a low-voltage source, a high-voltage interlock loop (HVIL) switch, and at least one control module. The low-voltage source provides a low-voltage power that is less than the HV power. The HVIL switch is in communication with the low-voltage source. The HVIL switch includes a reed relay and a magnetic element. The magnetic element is selectively positioned within an actuation distance from the reed relay. (US9327601 B2 2016.)

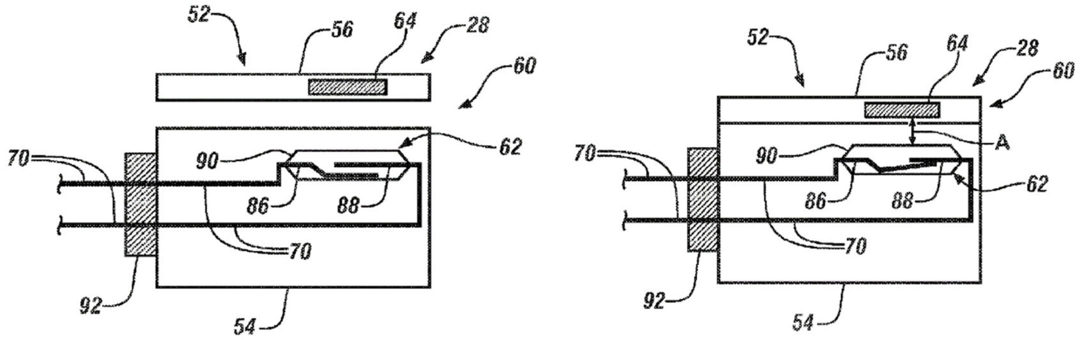


Figure 26. Basic idea about reed relay based on HVIL switch (US9327601 B2 2016)

The HVIL switch is in a closed circuit condition when the magnetic element is positioned within the actuation distance from the reed relay, and is in an open circuit condition when the magnetic element is positioned outside of the actuation distance from the reed relay. The at least one control module is in communication with and monitors the HVIL switch.” (US9327601 B2 2016.)

4.5.3 HV System Activation (KL15_hybrid)

DIN 72552 defines automobile electric terminal numbers. Traditionally number 15 have been “battery + from ignition switch”. DAF propose new signal name “KL15_hybrid” in their documentation. It requires a controlled start up and shut down behavior of the HV system. At the start up the hybrid controller (or energy manager) must take care of a sequential startup of the vehicle when the contact switch is turned on. First, the LV systems must be start up via KL15_ctrl before the HV systems will be start up via KL15_hybrid. When shutting down the hybrid controller sequence should be vice versa. It is necessary that each HV component has an active bleeding resistor to bleed the HV capacitors within 2 sec below 60 V_{DC} after HV system has shut down. (DAF 2012.)

5 DESIGN CONSIDERATIONS FOR HV SYSTEMS

Previous chapters introduce different types of the components in a basic level, which are needed when designing or manufacturing wiring harnesses, electrical centers or control units to electric vehicles. This chapter gathers different types of the design rules that are good know and understand when designing, and selecting parts for high voltage environments.

5.1 Differences in 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 the protective circuits and detection systems and additional measures put in place if required. Whilst it is advisable to galvanic separate different LV voltage levels, galvanic isolation is imperative between HV and LV system(s). The maximum protection can be provided by the spatial separation of the circuits to ensure as few physical contact points as possible, which eliminate the risk of a short circuit almost entirely. (ZVEI 2016.)

According to the ZVEI document “Voltage Classes for Electric Mobility” voltage levels in the HV commercial vehicles variate depending on the components type from 24 V_{DC} to 880 V_{DC}. With power semiconductors the voltage rating could be up to 1200 V_{DC}. Complete table can be found in Appendix 1.

5.2 Insulation requirements in HV system

The maximum allowed dimension of the electric centrals is always given in requirements. Customers are also willing to under-size boxes which are why it is important to understand physical limitations. Common insulation materials in low voltage electrical centers are: Air, PA-66 30% GFR (Polyamide-Nylon 6,6 – 30% Glass Fiber Reinforced) or PA-6 15% GFR and FR-4 (PCB base material).

High voltages impose severe stress on all connection system components. Insulation that is perfectly adequate at 12 V, may rapidly degrade or fail altogether at 12 kV. In general, as voltage increases, a corona forms around an HV conductor followed by dielectric breakdown, leading to arcing or catastrophic failure.

5.2.1 Clearance and Creepage Distances

Minimizing the risk of failure in the high-voltage equipment and give an adequate safety margin, conductors carrying high voltages must maintain a certain minimum distance separation. These distances, called clearance and creepage, vary by application and are specified in the appropriate safety standard. (Arrow 2017.)

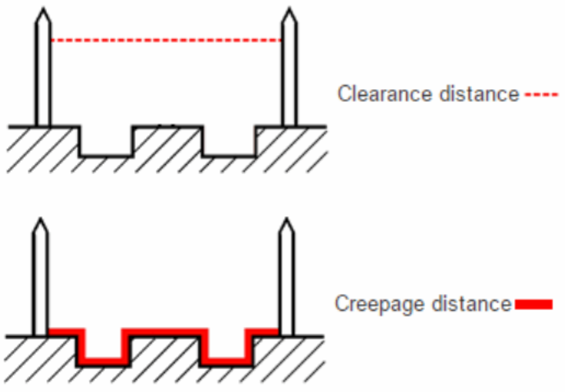


Figure 27. Clearance and creepage (Arrow 2017)

The clearance distance is the shortest distance between two conductive parts such as connector pins measured through air. An adequate clearance distance helps prevent dielectric breakdown between pins caused by air ionization. The dielectric breakdown level is also influenced by relative humidity, temperature, and the degree of the pollution in the environment. (Arrow 2017.)

The creepage distance is the shortest path between two conductive parts (or between a conductive part and the binding surface of the equipment) measured along the surface of the insulation material. A proper and adequate creepage distance protects against tracking, a process that produces a partially conducting path of localized deterioration on the surface of an insulating material as a result of the electric discharges on or close to an insulation surface. The creepage distance is equal to or larger than the clearance distance. (Arrow 2017.)

The Comparative Tracking Index (CTI) is used to measure the electrical breakdown (tracking) properties of the insulating material. For a given application, the minimum creepage distance required by safety agencies such as UL is dependent on the insulator’s CTI value. (Arrow 2017.)

5.2.2 Pollution Degree

The pollution degree can have a major impact on connectivity because clearance and especially creepage distances increase dramatically with the pollution degree. It is divided into four categories (1-4).

- **Pollution degree 1**: No pollution or only dry. The pollution has no influence (example: sealed or potted products).

- **Pollution degree 2**: Normally only nonconductive pollution occurs. Occasionally a temporary conductivity caused by condensation must be expected (example: product used in typical office environment); Typical usage: office and household environment.

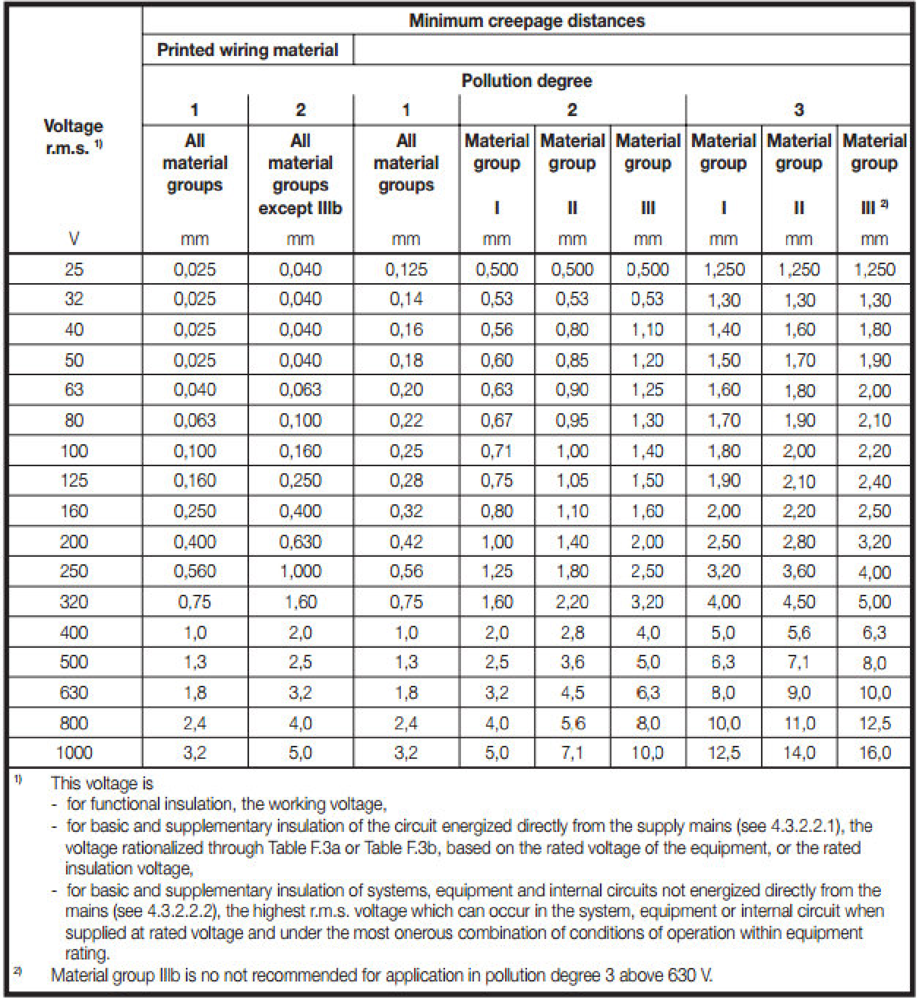
- **Pollution degree 3**: Conductive pollution occurs, or dry, nonconductive pollution occurs that becomes conductive due to expected condensation (example: products used in heavy industrial environments that are typically exposed to pollution such as dust). Typical usage: industrial environment.

- **Pollution degree 4**: Pollution generates persistent conductivity caused, for instance, by conductive dust or by rain or snow. (Brucchi & Peinhopf 2012.)

For example, D-subminiature (D-sub) connectors are commonly used in many applications. They are available from many vendors and are inexpensive. The distance between the connector pin and the ground shield is about 1.6 mm. This distance meets the UL creepage safety standards for both pollution degree 1 (0.3 mm) and pollution degree 2 (1.6 mm) environments at 150 V. For 300 V operations, the creepage distance for pollution degree 2 increases to 3.0 mm, so the connector meets safety standards only if used in a pollution degree 1 environment. Therefore, within a typical test environment - which is classified as degree 2—using a D-sub connector above 150 V does not meet applicable safety standards and is considered unsafe. (Arrow 2017.)

Minimum creepage distances in different pollution degrees depending on voltages from 25 V to 1000 V are given in Table 3. Material groups and correlation for CTI values are described in chapter 5.2.5 Comparative Tracking Index CTI.

Table 3 Creepage requirements depending on working voltage and package material group (IEC 60664-1)



Voltage r.m.s. [1]	Minimum creepage distances								
	Printed wiring material								
	Pollution degree								
	1	2	1	2			3		
	All material groups	All material groups except IIIb	All material groups	Material group I	Material group II	Material group III	Material group I	Material group II	Material group III [2]
V	mm	mm	mm	mm	mm	mm	mm	mm	mm
25	0,025	0,040	0,125	0,500	0,500	0,500	1,250	1,250	1,250
32	0,025	0,040	0,14	0,53	0,53	0,53	1,30	1,30	1,30
40	0,025	0,040	0,16	0,56	0,80	1,10	1,40	1,60	1,80
50	0,025	0,040	0,18	0,60	0,85	1,20	1,50	1,70	1,90
63	0,040	0,063	0,20	0,63	0,90	1,25	1,60	1,80	2,00
80	0,063	0,100	0,22	0,67	0,95	1,30	1,70	1,90	2,10
100	0,100	0,160	0,25	0,71	1,00	1,40	1,80	2,00	2,20
125	0,160	0,250	0,28	0,75	1,05	1,50	1,90	2,10	2,40
160	0,250	0,400	0,32	0,80	1,10	1,60	2,00	2,20	2,50
200	0,400	0,630	0,42	1,00	1,40	2,00	2,50	2,80	3,20
250	0,560	1,000	0,56	1,25	1,80	2,50	3,20	3,60	4,00
320	0,75	1,60	0,75	1,60	2,20	3,20	4,00	4,50	5,00
400	1,0	2,0	1,0	2,0	2,8	4,0	5,0	5,6	6,3
500	1,3	2,5	1,3	2,5	3,6	5,0	6,3	7,1	8,0
630	1,8	3,2	1,8	3,2	4,5	6,3	8,0	9,0	10,0
800	2,4	4,0	2,4	4,0	5,6	8,0	10,0	11,0	12,5
1000	3,2	5,0	3,2	5,0	7,1	10,0	12,5	14,0	16,0

[1] This voltage is
- for functional insulation, the working voltage,
- for basic and supplementary insulation of the circuit energized directly from the supply mains (see 4.3.2.2.1), the voltage rationalized through Table F.3a or Table F.3b, based on the rated voltage of the equipment, or the rated insulation voltage,
- for basic and supplementary insulation of systems, equipment and internal circuits not energized directly from the mains (see 4.3.2.2.2), the highest r.m.s. voltage which can occur in the system, equipment or internal circuit when supplied at rated voltage and under the most onerous combination of conditions of operation within equipment rating.

[2] Material group IIIb is no not recommended for application in pollution degree 3 above 630 V.

5.2.3 Corona Discharge

A corona discharge is an electrical discharge brought on by the ionization of air surrounding the conductor that is electrically charged. The corona will occur when the strength (potential gradient) of the electric field around a conductor is high enough to form a conductive region, but not high enough to cause electrical breakdown or arcing to nearby objects. This can occur at voltages as low as 300 V. The corona can also occur due to the ionization of air within a void in a dielectric or interface inside of the connector. While corona is a low-energy process, over long periods of time, it can substantially degrade insulators, causing a system to fail due to dielectric breakdown. To minimize corona effects in connector design, it is important to maximize the distance between conductors that have large voltage differentials, use conductors with large radii, avoid designs that have sharp points or sharp edges, and use dielectrics without voids. (Arrow 2017.)

5.2.4 Arcing and Dielectric Breakdown

A dielectric breakdown occurs when a charge buildup exceeds the electrical limit or dielectric strength of the material. An electric arc, or arc discharge, is an electrical breakdown of the gas that produces an ongoing plasma discharge, resulting from a current through normally nonconductive media such as air. The dielectric strength of air is approximately 3 kV / mm. Its exact value varies with the shape and size of the electrodes and increases with the pressure of the air. (Hong 2000.)

In the case of a solid medium such as a dielectric, a dielectric breakdown occurs when the voltage stress is significant enough to cause an arc through the dielectric between the conductor and ground. This failure is catastrophic because the current flow through the dielectric leaves voids filled with carbon and the dielectric will no longer be able to withstand the required voltage. (Arrow 2017.)

5.2.5 Comparative Tracking Index CTI

The Comparative Tracking Index or CTI is used to measure the electrical breakdown (tracking) properties of the insulating material. The comparative tracking index is expressed as that voltage which causes tracking after 50 drops of 0.1 percent ammonium chloride solution have fallen on the material. The results of testing the nominal 3 mm thickness are considered representative of the materials performance in any thickness (according to IEC60112).

	CTI
Material Group I	≥600
Material Group II	≥400 through < 600
Material Group IIIa	≥175 through < 400
Material Group IIIb	≥100 through < 175

Performance Level Categories (PLC) was introduced to avoid excessive implied precision and bias.

Tracking index (V)	**PLC**
≥600	0
≥400 through < 600	1
≥250 through < 399	2
≥175 through < 249	3
≥100 through < 174	4
< 100	5

Typically, mold compounds for discrete semiconductor packages belong to material group II (400-600V) (Brucchi & Peinhopf 2012). Some CTI values of the different plastics are shown in Chart 1.

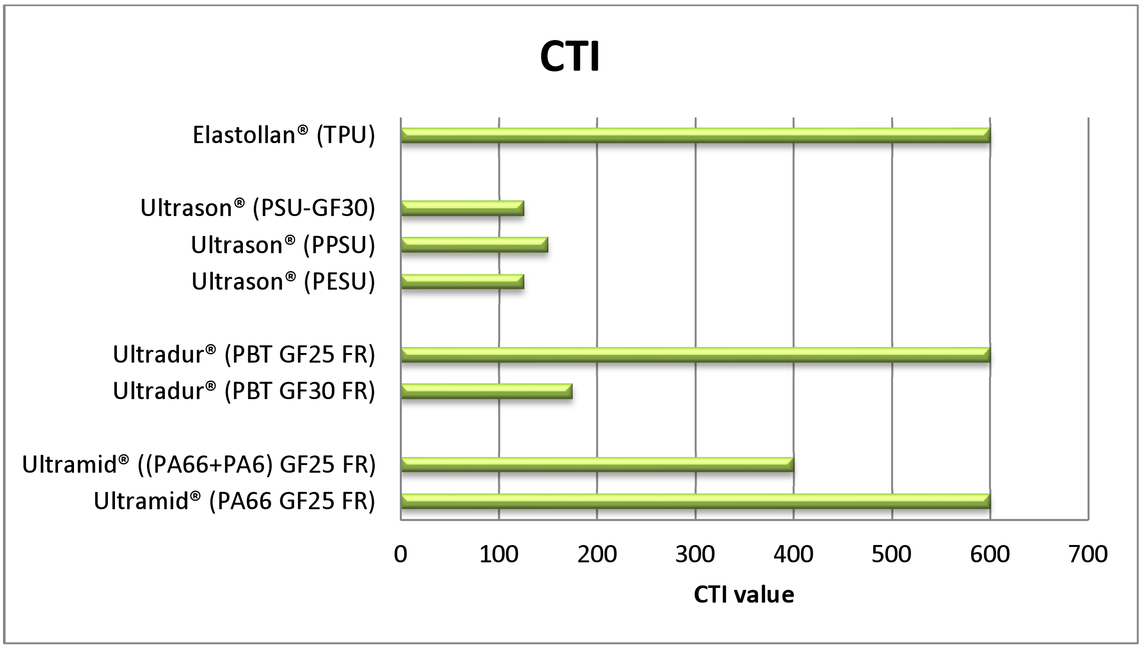
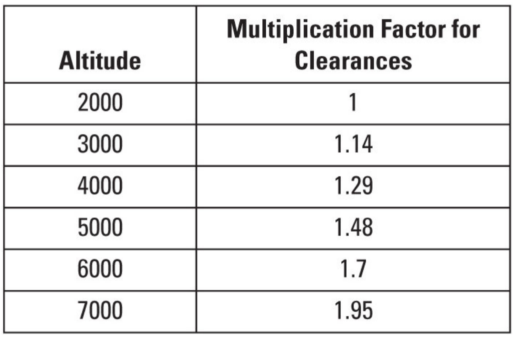


Chart 1 Some CTI values of the different plastic types (BASF 2016)

5.2.6 Altitude

At the higher altitudes of 2000 to 5000 meters above sea level, the air pressure is lower. Therefore, peak over voltages, such as surge or temporary overvoltage, can more readily cause arching between the isolator pins. Equipment operating at high altitudes requires greater spacing between pins (more clearance). Table 4 shows the multiplication factors by which clearance must be increased at higher altitudes to prevent arcing per IEC 60664-1. (Power Electronic Tips 2015.)

Table 4 Multiplication factors for clearances at higher altitudes (IEC 60664-1)



Altitude	Multiplication Factor for Clearances
2000	1
3000	1.14
4000	1.29
5000	1.48
6000	1.7
7000	1.95

5.3 Plastics

Plastics used in electrical applications have to show excellent electrical performance, good mechanical properties as well as high dimensional stability under heat. In daily operation, they have to guarantee insulation and therefore secure handling. They have to reduce fire risk in the event of an electrical defect or exposure to external sources of the ignition. With many applications, the plastic is used for designing the exterior of the components as well. This is why design requirements, e.g. for surface quality, haptics and colors are becoming more and more important. In HV applications the CTI value is important as stated in chapter 5.2.5 Comparative Tracking Index CTI. (BASF 2016.)

Polyamide (PA) has good electrical insulation properties, useful sliding friction performance, and excellent mechanical strength. It is available in a wide range of the flame-retardant grades, and is therefore used in almost every sector of the industrial control units, connection technology, and electronics as well as in household appliances as shown in Table 5. CTI values vary between 400 and 600. That is why some of polyamides are suitable selections than others. (BASF 2016.)

Polybutylene terephthalate (PBT) has a specific combination of the properties making it an ideal material for particular applications in electrical engineering and electronics. It shows not only high stiffness and good thermal resistance but also exceptional dimensional stability and excellent long-term electrical and thermal performance. Preferred application sectors are electrical systems in rail vehicles, circuit breakers, plug connectors and electronic switching elements for higher voltages (e. g. rail vehicles, alternative drives, and photovoltaic systems) as shown in Table 5. CTI values vary between 180 and 600, which mean that care is needed when selecting PBT as an insulation material to HV products. (BASF 2016.)

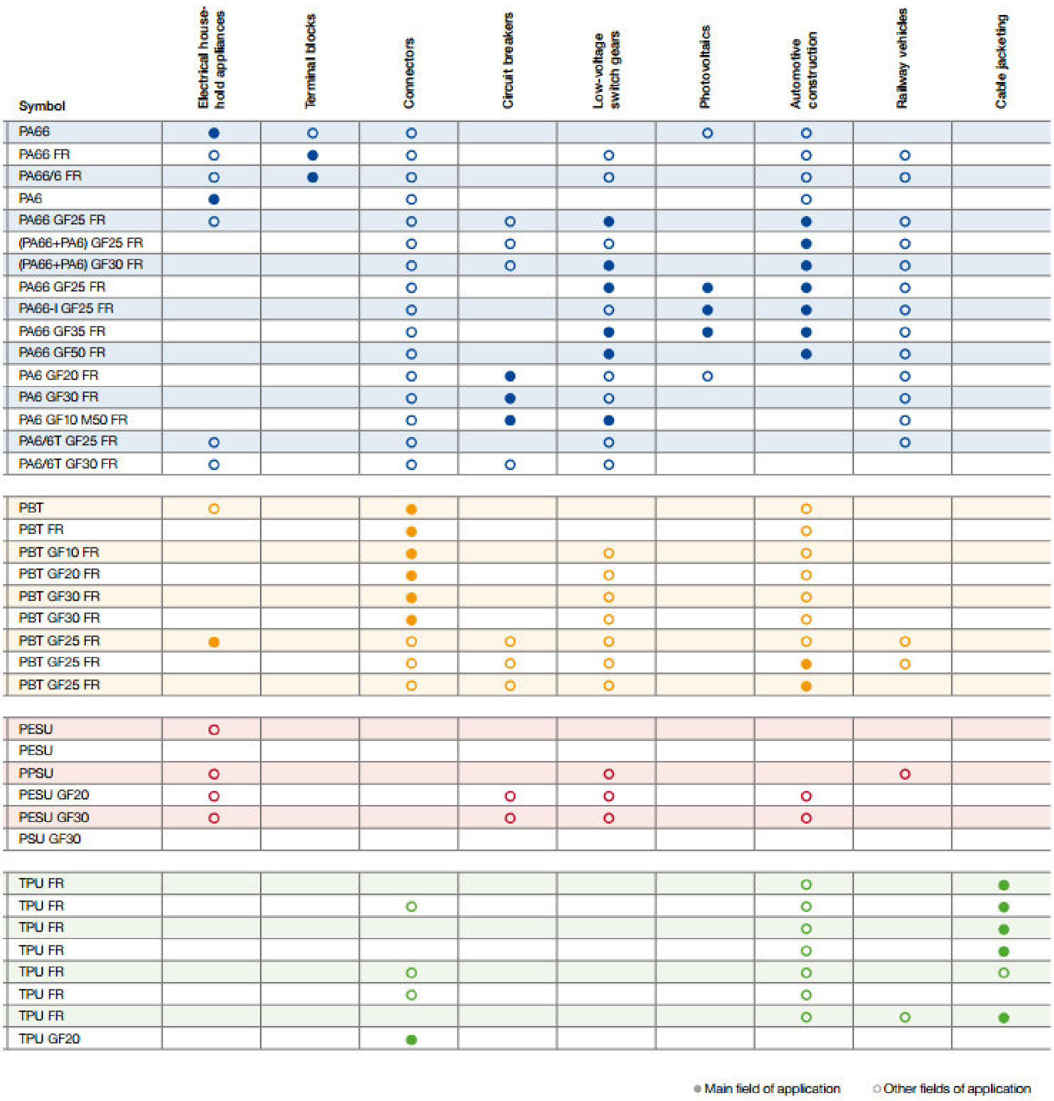
Polyethersulfone (PESU), polysulfone (PSU) and polyphenylsulfone (PPSU) are amorphous thermoplastics with high temperature resistance. The particular features are their high dimensional stability and good mechanical properties that are substantially independent of temperature. Typical examples of the applications (Table 5) for these plastics in electrical engineering and electronics are:

- Coil formers, plug connectors, parts for circuit breakers and relays
- Viewing windows for indicator lamps and switching boards, lamp sockets, lamp covers and reflectors
- Heat shields, sensors, chip carriers, chip trays

CTI values vary between 125 and 150 which mean that those are not suitable selection for HV applications. (BASF 2016.)

Thermoplastic polyurethane (TPU) has a versatile property profile that makes it an ideal material for applications in signal transmission and energy transfer. Besides a high level of the resistance to abrasion and mechanical wear TPU also has a wide range of strengths: The hydrolytic resistance and the outstanding low-temperature flexibility and resistance to microbes represent considerable advantages in particular for the polyether-based TPU grades used in industrial applications. The polyester-based TPU grades are noted above all for their resistance to oil and grease. CTI value is 600 and it is reliable selection for HV solutions. (BASF 2016.)

Table 5 Overview: Engineering plastics and possible applications (BASF 2016)



Symbol	Electrical house-hold appliances	Terminal blocks	Connectors	Circuit breakers	Low-voltage switch gears	Photovoltaics	Automotive construction	Railway vehicles	Cable jacketing
PA66	●	○	○			○	○		
PA66 FR	○	●	○		○		○	○	
PA66/6 FR	○	●	○		○		○	○	
PA6	●		○				○		
PA66 GF25 FR	○		○	○	●		●	○	
(PA66+PA6) GF25 FR			○	○	○		●	○	
(PA66+PA6) GF30 FR			○	○	●		●	○	
PA66 GF25 FR			○		●	●	●	○	
PA66-I GF25 FR			○		○	●	●	○	
PA66 GF35 FR			○		●	●	●	○	
PA66 GF50 FR			○		●		●	○	
PA6 GF20 FR			○	●	○	○		○	
PA6 GF30 FR			○	●	○			○	
PA6 GF10 M50 FR			○	●	●			○	
PA6/6T GF25 FR	○		○		○			○	
PA6/6T GF30 FR	○		○	○	○				
PBT	○		●				○		
PBT FR			●				○		
PBT GF10 FR			●		○		○		
PBT GF20 FR			●		○		○		
PBT GF30 FR			●		○		○		
PBT GF30 FR			●		○		○		
PBT GF25 FR	●		○	○	○		○	○	
PBT GF25 FR			○	○	○		●	○	
PBT GF25 FR			○	○	○		●		
PESU	○								
PESU									
PPSU	○				○			○	
PESU GF20	○			○	○		○		
PESU GF30	○			○	○		○		
PSU GF30									
TPU FR							○		●
TPU FR			○				○		●
TPU FR							○		●
TPU FR							○		●
TPU FR			○				○		○
TPU FR			○				○		
TPU FR							○	○	●
TPU GF20			●						

● Main field of application ○ Other fields of application

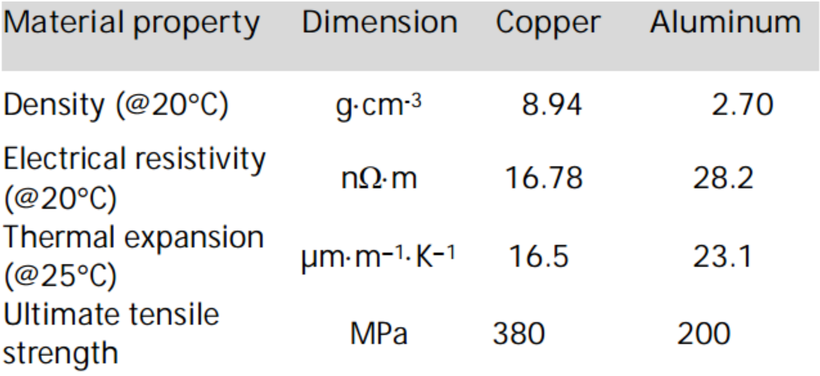
5.4 Main Conductive Materials Aluminum and Copper

When using materials as a conductor (most usual copper and aluminum), the following material properties are to be considered:

- Conductivity
- Tensile strength
- Coefficient of expansion / creep
- Weight

The material properties of pure copper and aluminum are given in Table 6 below. Properties vary depending alloy. (Siemens 2014.)

Table 6 Material properties of pure copper and aluminum (Siemens 2014)



Material property	Dimension	Copper	Aluminum
Density (@20°C)	$g\cdot cm^{-3}$	8.94	2.70
Electrical resistivity (@20°C)	nΩ·m	16.78	28.2
Thermal expansion (@25°C)	$\mu m\cdot m^{-1}\cdot K^{-1}$	16.5	23.1
Ultimate tensile strength	MPa	380	200

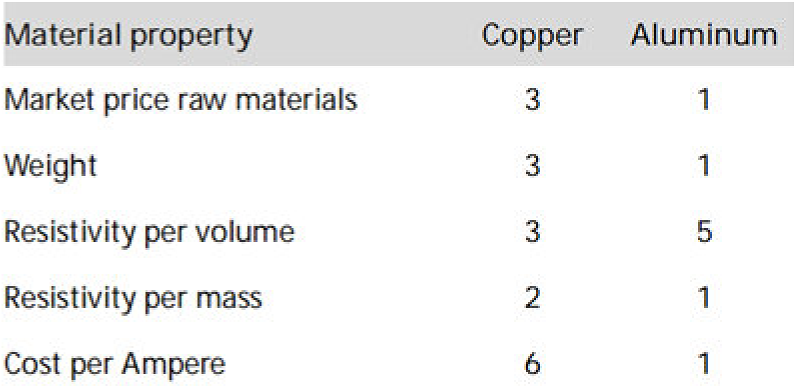
5.4.1 Feasibility

The comparison of the physical material properties is shown in Table 7. The Electrical resistivity ratio per volume of the copper compared to aluminum is 3 to 5. This means that aluminum conductor volume needs to be 68% bigger compared to copper to reach same current carrying capacity. (Siemens 2014.)

The densities of copper and aluminum has the ratio of 3:1, meaning that copper is about three times heavier than aluminum. Weight ratio is related to the electrical resistivity, which means that copper compared to aluminum is 2 to 1. This implies that per kg, aluminum is a two times better conductor than copper. (Siemens 2014.)

When considering the 2017 raw material prices – copper ($2.62/lb) vs. aluminum ($0.85/lb) ratio roughly 3 to 1 - combined with above physical material characteristics; result in a cost per amperage relation between copper and aluminum of about 6 to 1. (Prices: InvestmentMine 2017)

Table 7 Characteristic ratios between copper and aluminum (Siemens 2014)



Material property	Copper	Aluminum
Market price raw materials	3	1
Weight	3	1
Resistivity per volume	3	5
Resistivity per mass	2	1
Cost per Ampere	6	1

5.4.2 Tensile Strength

The tensile strength of the pure metals copper and aluminum is about 2:1 (Table 6). For electrical grade aluminum alloys this ratio is almost 1:1. This indicates that the tensile strength of aluminum conductors approaches that of copper conductors. Aside from the influence of connection components, it is mainly the increased tensile strength of the currently available aluminum conductor alloys that defines aluminum as a competitive alternative to copper. The 5 to 10% resistivity rise that results from the alloy's increased tensile strength is compensated with the increased conductor volume. (Siemens 2014.)

5.4.3 Oxidation

Both copper and aluminum will oxidize when exposed to outside air. The oxidation process of aluminum will start directly when the bare metal is brought in contact with air. Furthermore, there is a big difference in the material properties of the oxide layer that forms when the metals oxidize. The aluminum-oxide layer is impregnable to oxygen, which will stop the oxidation process as soon as a very thin (µm) thick layer has formed. Copper-oxide is permeable to oxygen. Consequently, the oxidation process will continue until all copper is consumed. Aluminum oxide is a very good insulator (volume resistivity >1.1017 Ω.m). Therefore, in bus-bar applications where contact surfaces are bolted together, the oxidation of the contact surface is not an option. To prevent oxidation, aluminum conductors can be tin (Sn) plated over the full length. The sole purpose of this plating is to ensure a durable low resistant surface at the contact points. As the conductors are tin plated over the full length, there are no direct aluminum-to-aluminum contact surfaces. In case the contact surface is damaged or scratched exposing the bare metal, the rapid aluminum oxidation prevents the damage from growing over time. As the contact surface area is over dimensioned, the remaining contact surface will ensure the required conductive capabilities. (Siemens 2014.)

5.4.4 Galvanic Corrosion

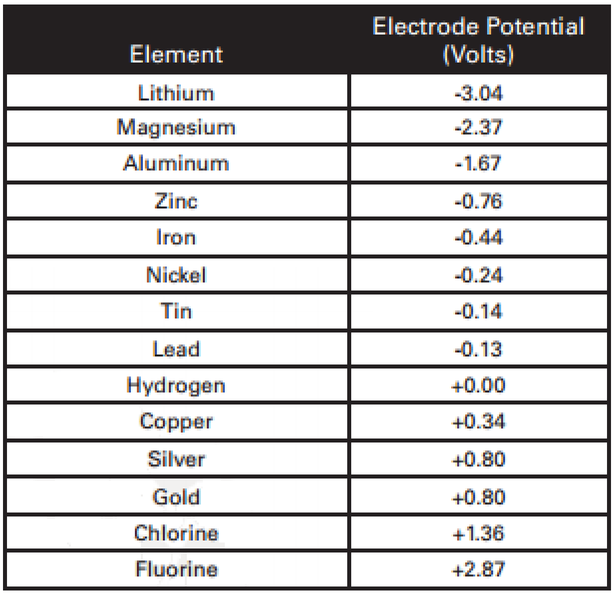
Unless exposed to high carbon content (cinder fill), galvanic corrosion does not usually arise as an issue for copper due to the noble nature of the metal. Aluminum is more reactive metal than Copper. As a result, galvanic corrosion is the most commonly occurring form of corrosion in the aluminum electrical applications. Often used as an electrical conductor in either cable form, connector form or as the busbar in panels, aluminum will require tin-plating and connectors to mitigate galvanic reaction when connected to copper. An oxide-inhibiting compound should also be used to ensure moisture (electrolyte) does not reach the contact surface and facilitate galvanic reaction. (Mak A.)

The best way to eliminate galvanic corrosion is to:

- Select metals that are close together in the galvanic series
- Isolate the metals from each other using insulating materials
- Eliminate the presence of electrolyte on the metal surface
- Maintain a large surface anodic area in relation to the cathodic area. (Mak A.)

Table 8 shows the potential difference measured between various metals and the standard hydrogen electrode.

Table 8 Electrode potential of various metals versus the standard hydrogen electrode



Element	Electrode Potential (Volts)
Lithium	-3.04
Magnesium	-2.37
Aluminum	-1.67
Zinc	-0.76
Iron	-0.44
Nickel	-0.24
Tin	-0.14
Lead	-0.13
Hydrogen	+0.00
Copper	+0.34
Silver	+0.80
Gold	+0.80
Chlorine	+1.36
Fluorine	+2.87

Understanding galvanic corrosion has led to the use of metals in the galvanic series for cathodic protection. For example, electrically connecting buried steel pipe with zinc, which is more anodic, allows the zinc to corrode before the steel. It is offered up as a sacrificial anode and limits the corrosion of the steel pipe until all of the zinc is consumed. (Mak A.)

5.4.5 Other Metals

Brass is an alloy of copper and zinc. Differentiation is made between pure (binary) brass and special brass. The material CuZn39Pb3 is the basic alloy for metal cutting and particularly suited for working on automatic machines. Brass possesses good resistance to water, steam, salt water and many organic liquids, however, not to oxidizing acids. Under certain conditions (water with high Cl content, low carbon hardness and low flow rates), corrosion may be incurred in the form of dezincification. Galvanized nickel-plating can be used as a surface refinement. Due to their special mechanical and chemical properties, nickel deposits are suitable for protection against wear and corrosion. Nickel can be polished well and it is magnetic. (Pflitsch 2014.)

Stainless steel is a common name for different steel alloys. Two well-known grades are named A2 and A4. Both only possess corrosion resistance with a metallically clean surface. That is why the layers of scale and tarnished paints incurred in thermoforming, thermal treatment or welding, must be removed prior to use. Stainless steels are characterized to be special resistance to chemically corroding watery media. The chemical resistance of the stainless steel A2 / A4 is presented in Appendix 2. (Pflitsch 2014.)

A2 is austenitic steel and it is non-magnetic. The chromium provides a corrosion and oxidation resistance, however it can tarnish. It is immune to most organic chemicals and dyestuffs also a wide variety of inorganic chemicals. However, for marine conditions more resistance to corrosion is needed. Adding molybdenum (2-3 %) to the mix provides this extra cover – and gives us the A4 grade. (Graphskill 2011.)

A4 grade then is also austenitic, non-magnetic and suitable for all the situations as A2 but has the added advantage of being suitable for marine solutions. That is why it is often called as Marine Grade stainless steel. The molybdenum increases the corrosion resistance to withstand attack from many industrial chemicals and solvents and of course, chlorides. (Graphskill 2011.)

5.5 HV Wires & Cables

There are practically two different types of the HV cables in use (Figure 28). Individually shielded cables are used when connected devices has high current consumption. Bundle braided shielding can be used if space is limited, tight bending is needed etc.

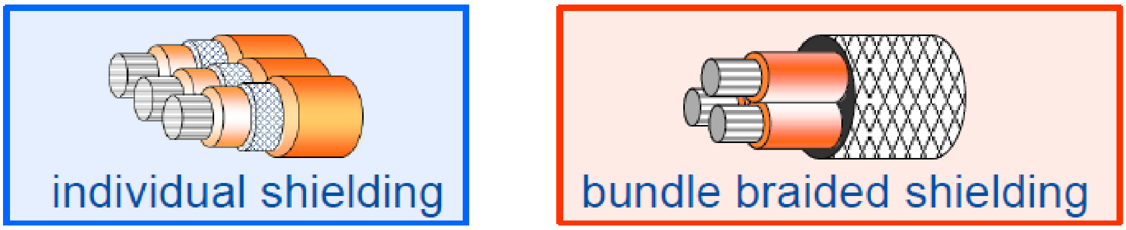


Figure 28. Differences between individual and bundle braided shielding (Sumitomo 2014)

Sumitomo Electric Group has patented “aluminum pipe harness” product, where full (or a part of the) wiring harness is covered with a rigid aluminum pipe Figure

29. This helps to prevent fixation points in vehicle and allows new possibilities for routing. Pipe harness can be installed very near of the exhaust pipe in hybrid vehicles.

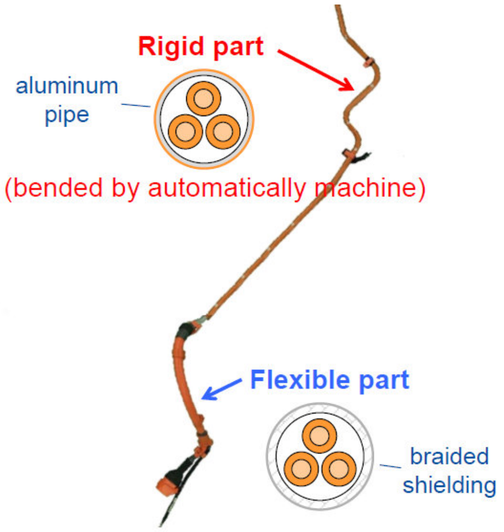


Figure 29. Aluminum pipe harness (Sumitomo 2014)

From manufacturing point-of-view, higher loads usually mean larger wire cross-sections and separate installation requirements mean independent wiring (HV and LV systems). Aluminum wires require larger bending radius. Necessary old work methods with copper wires are not valid anymore. The aluminum wires and cables require the separate production environment because of immediately oxidation. (Sumitomo 2014.)

5.5.1 Requirements for HV Wiring

HV wiring must comply with ISO 14572 standard named “*Round, sheathed, 60 V and 600 V screened and unscreened single- or multi-core cables - Test methods and requirements for basic- and high-performance cables*”. All HV harnesses shall be identified with labels at each connector end. The label must contain at least the following information:

1. The yellow warning sign with thunderbolt (Figure 30)

Figure 30. Warning sign

2. The words: CAUTION, WARNING or DANGER
3. The function name of the connector
4. The highest voltage level in the harness
5. Identification numbers (Customer no, supplier no, manufacturing date, etc.).

All HV wiring must have an orange base color (Munsell 8.75R5.75/12.5 or 8.8R5.8/12.5, according ISO 6469-3) and must be covered with an orange corrugated tube for extra mechanical protection. All cables and wires connecting electrical power components (e.g. motor, generator, inverter and RESS) must have an additional conductive shield that is insulated from the HV power circuit. Conductive shielding must be connected to the chassis ground. If there is an insulation failure or a broken power wire, an electronic monitoring system must detect the isolation defect. (DAF 2012.)

5.5.2 Ingress Protection Requirements

To fulfill coincidental requirements of tight IP classes with EMC shielding and high current transportation cost-effective way is to select metallized / metal cable gland with ring terminal (Figure 31).

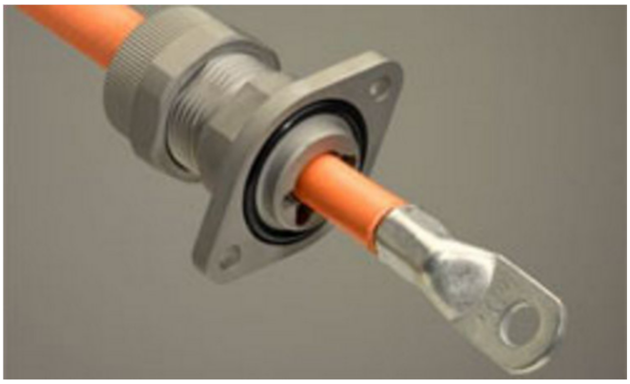


Figure 31. MAX-LOC® -connector by Molex (Molex 2015)

O-ring (black in Figure 31) provides required IP-class (even IP69K) when cable gland is tightened by screws to the metallized wall of casing. Metallized casing is needed to reduce disruptive EMI and RFI.

Exploded view (Figure 32) presents internal construction of the cable gland.

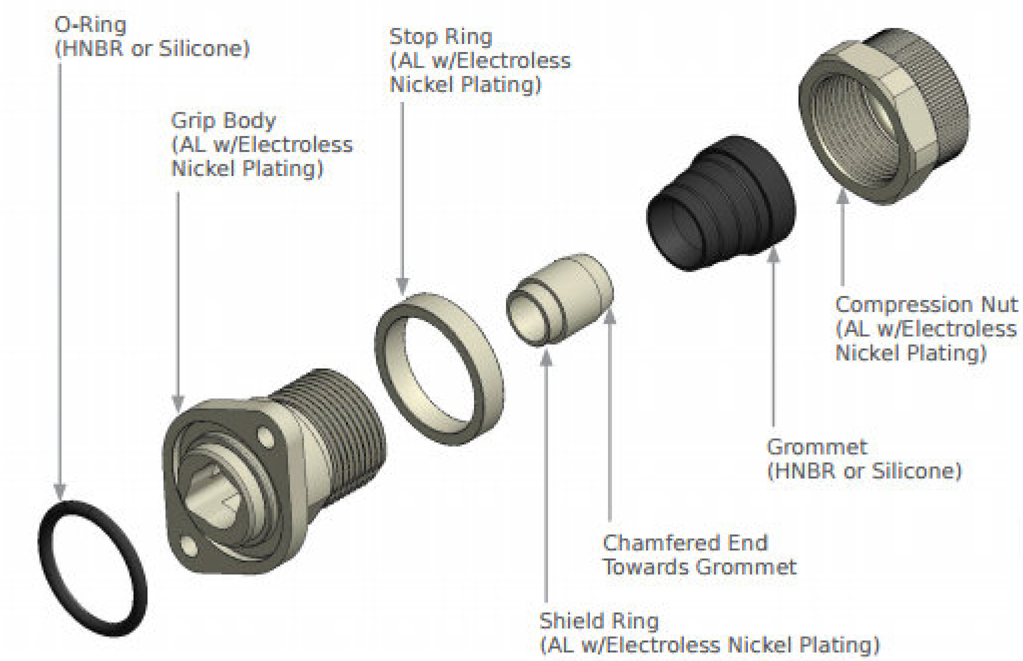


Figure 32. Exploded view of MAX-LOC® -connector by Molex (Molex 2015)

Screen of the shielded cable in Figure 33 between the chamfered end and grommet. The structure of connector together with a shielded cable provides required EMC protection in high voltage system with high currents.

Figure 33. Component assembly view with shielded cable (Molex 2015)

The required IP class can be reached also using sealed connector housings. It is convenient if for example shape of the enclosure or the location of it will not allow opening the enclosure cover. The sealing mechanism is very similar in both LV and HV connectors. Several manufacturers provide connectors with similar features. Following represents TE’s AMP+ HVP 800 connector and their sealing concept. Radial seal is inside orange rectangular in Figure 34.

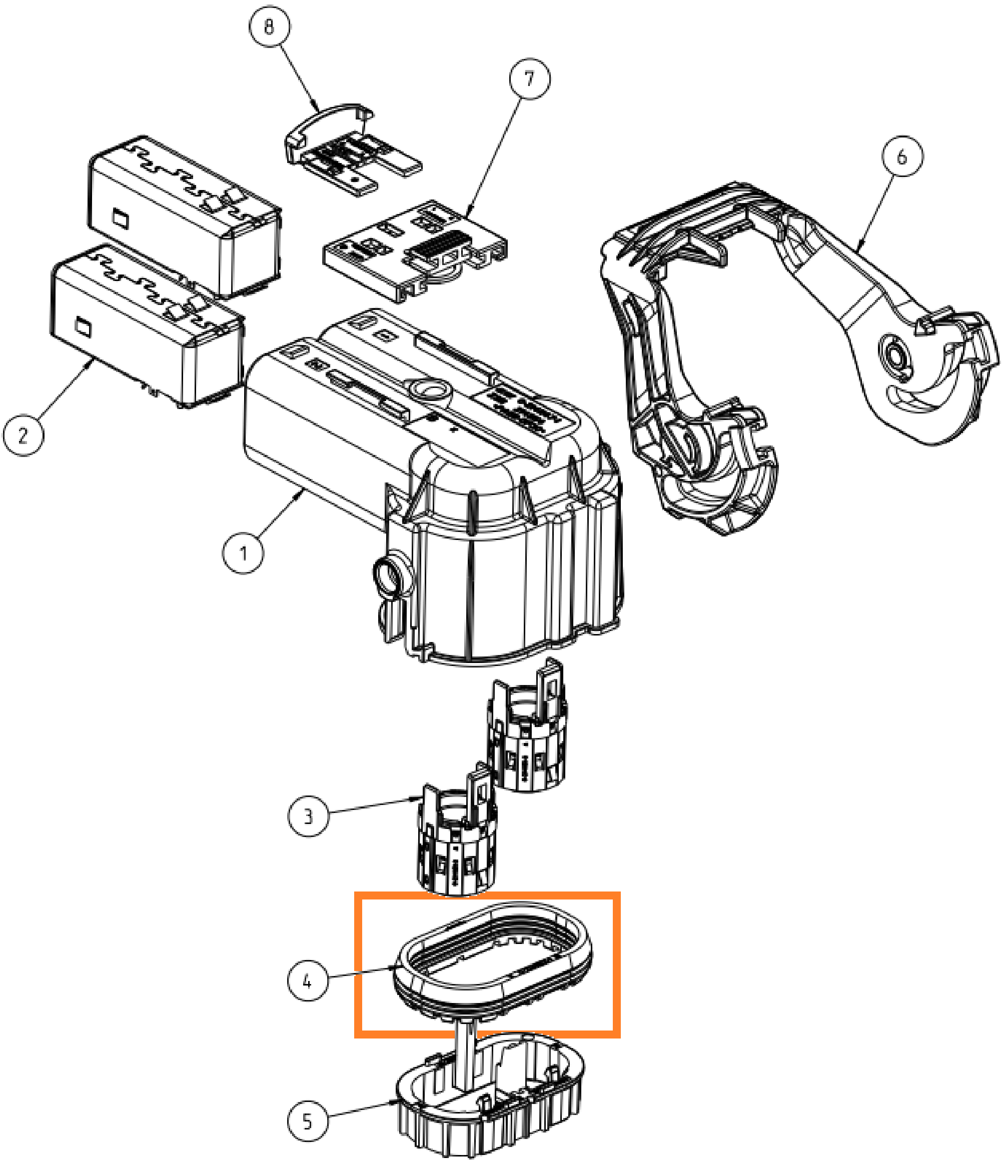


Figure 34. Exploded view of AMP + HVP 800 90 angled connector (TE Connectivity 2012)

AMP+ HVP 800 –series connectors (Figure 35) are rated up to 1000 V and 250 A. Temperature range is from -40 °C to +140 °C. The connector is EMC shielded 360° from a wire to the device. IP rating is IP67 even IP6k9k when mated and IP2xb when unmated. (TE Connectivity 2017.)

Figure 35. AMP+ HVP 800 HV connector system (TE Connectivity 2017)

5.5.3 Charging Connectors

Charging connectors and pin orders are already standardized. There is also some design rules, which are good to know. Each external power connection must have a sensing contact or electronic impedance sensing to turn off the HV for the connection when no equipment is connected. The socket type may comply with IEC 60309-1 norm when any industrial standard equipment may be connected and may not comply with IEC 60309-1 norm when only specified equipment is allowed to connect. The IEC 60309 norm socket to be used must be 5-pin (3P + N + PE), with at least IP67 rating if used on the chassis. Although N is normally not connected, it is more common for commercial equipment to have a 5-pin connector. An optical indication must be visible on or near the socket to show when the socket is powered on. The multi wire cable to this socket must be orange and have a metal screen shield. As an extra mechanical protection, an orange corrugated tube must be used to cover this cable. (DAF 2012.) Internal connection of the charging connectors is described in Appendix 4.

5.5.4 Permitted Voltage Drop

Standard IEC 60364-5-52 called “Low-voltage electrical installations – Part 5-52: Selection and erection of the electrical equipment – Wiring systems” recommends permitted voltage drop a maximum value of 4%. This value applies to normal operation, and does not take account of the devices, such as motors, that can generate high inrush currents and voltage drops. More restrictive values may be required for the link between the transformer and the main breaking or protection device.

If the voltage drop is greater than the permitted limits, it is advisable to increase the cross-section of the conductors until the voltage drop is below the specified values. When the main wiring systems of the installation are longer than 100 m, the permitted voltage drop limits can be increased by 0.005% per meter above 100 m, but this additional amount must not itself exceed 0.5%

There is no exact standard, which define the allowed voltage drop in vehicles. Depending on manufacturers, there are different solutions in use and exact requirements are impossible to define. Cables, connectors and safety components in power train have their own resistances which variates depending on environment temperature, operating conditions, aging etc.

Fluke gives some maximum voltage drop values for low voltage system:

- 0.00V across a connection
- 0.20V across a wire or cable
- 0.30V across a switch
- 0.10V at a ground. (Fluke 2017.)

5.6 Inrush Current Limitation

To prevent high current peaks during startup (for charging the input capacitors), measures must be taken to limit the inrush currents, e.g. by the use of a pre-charge resistor. If more than one inverter and/or converter are part of the HV electrical system, measures must be taken to prevent that the input filters (capacitors) interfere with each other. In practice, this means that series diodes must be used to prevent current flow between the capacitor banks of the different inverters / converters. (DAF 2012.)

Inrush currents from capacitors are the most common cause of the contactor failure. Capacitors that are not fully charged can result in excessive loads being switched. Since the discharge of most capacitors is almost instantaneous, this type of event is sometimes overlooked or not recognized. A capacitor that has a 80% state of charge can result in twice the current of the capacitor that is charged to 90%. Gigavac recommends charging the capacitor to a 95% state of charge. Lower states of charge can result in currents of hundreds or thousands of amps. These currents can be measured with a current clamp or shunt and an oscilloscope set to a resolution of 0.05 ms. One way to quickly diagnose a tac weld (contacts stuck in closed position) is to cycle the coil 10 to 20 times. A typical tac weld will break as a result of this coil actuation. (Gigavac 2017.)

Peak inrush current can be calculated using formula:

$$I = C\left(\frac{\Delta V}{\Delta T}\right) \qquad (7)$$

Calculating with example values:

C = 11000 µF
ΔV = 800 V
Δt = 1 ms

We can get inrush current as high as 8800A, which immediately will blow up 15A rated fuse. If we can slow down Δt to be 1s current is only 8.8A.

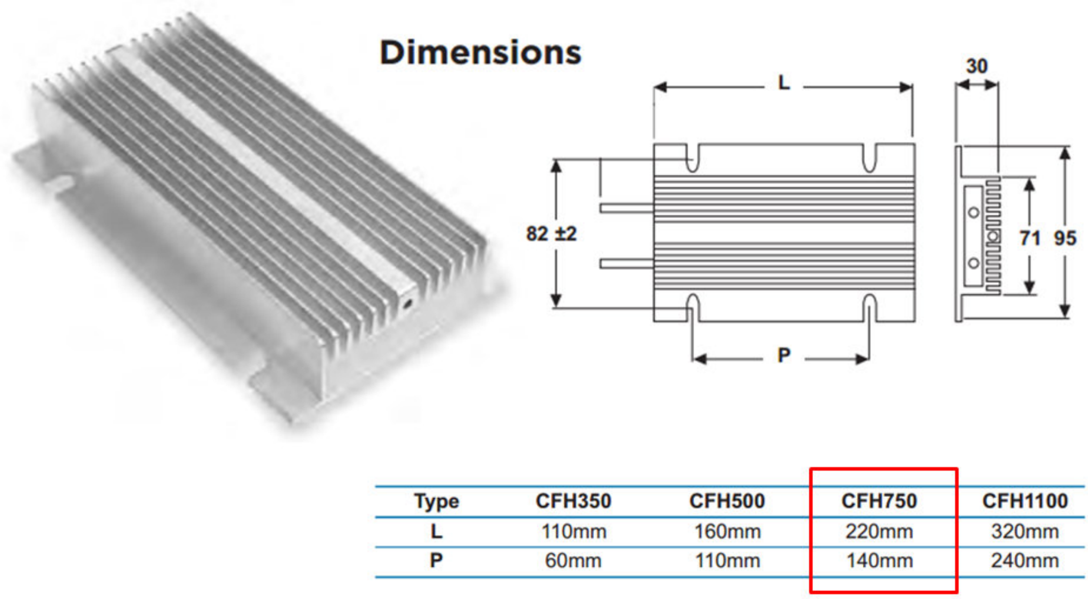
After a time period “$5x\tau$” capacitor is reached its fully charged state. Fully charging time can be calculated using formula $\tau \approx 5RC$. It can be converted to mode:

$$R = \frac{\tau}{5C} \quad (8)$$

Using values $\tau = 1s$ and C=11 000 µF resistance is 18Ω.

Power dissipation (P=UxI) with values U=800 V and I=8.8 A is approximately 7kW over 1 s. This leads the fact that resistor selection needs attention. Regular power resistors with 50 W to 300 W power rating cannot be used.

TE Connectivity has aluminum housed power resistors called CFH series. Type CFH750 can withstand 8 kW power dissipation during 5 s. Its nominal power dissipation is 1300 W at 25℃ with heatsink. Physical dimension is (LxWxH): 220 x 95 x 30 mm.

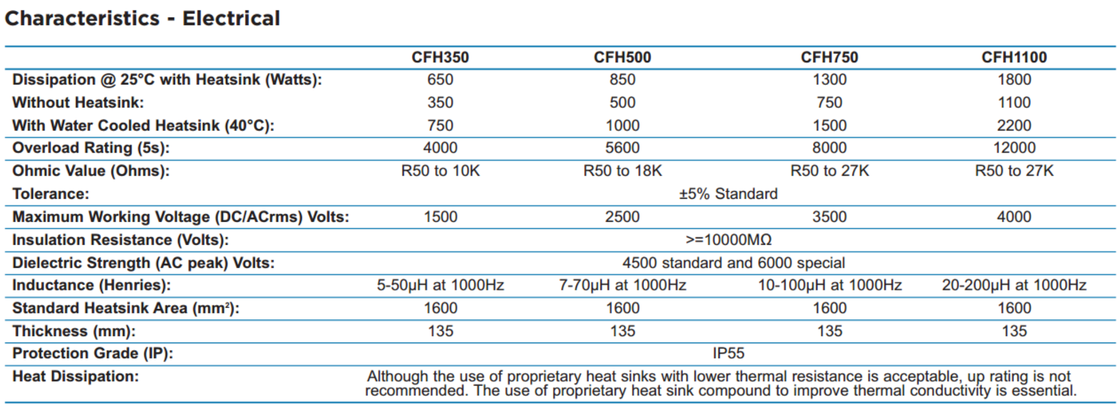


Type	CFH350	CFH500	CFH750	CFH1100
L	110mm	160mm	220mm	320mm
P	60mm	110mm	140mm	240mm

Figure 36. Aluminum housed power resistor CFH series (TE Connectivity 2011, 10.)

The biggest version is CFH1100 which power dissipation is 1800 W @ 25℃ with heat sink. It can be overloaded for 5 s even 12 kW.

Table 9 Electrical characteristics of CFH series (TE Connectivity 2011, 10.)



Characteristics - Electrical

	CFH350	CFH500	CFH750	CFH1100
Dissipation @ 25°C with Heatsink (Watts):	650	850	1300	1800
Without Heatsink:	350	500	750	1100
With Water Cooled Heatsink (40°C):	750	1000	1500	2200
Overload Rating (5s):	4000	5600	8000	12000
Ohmic Value (Ohms):	R50 to 10K	R50 to 18K	R50 to 27K	R50 to 27K
Tolerance:	±5% Standard			
Maximum Working Voltage (DC/ACrms) Volts:	1500	2500	3500	4000
Insulation Resistance (Volts):	>=10000MΩ			
Dielectric Strength (AC peak) Volts:	4500 standard and 6000 special			
Inductance (Henries):	5-50μH at 1000Hz	7-70μH at 1000Hz	10-100μH at 1000Hz	20-200μH at 1000Hz
Standard Heatsink Area (mm^2):	1600	1600	1600	1600
Thickness (mm):	135	135	135	135
Protection Grade (IP):	IP55			
Heat Dissipation:	Although the use of proprietary heat sinks with lower thermal resistance is acceptable, up rating is not recommended. The use of proprietary heat sink compound to improve thermal conductivity is essential.			

5.7 PCB Clearance Requirements

The spacing distance between components that is required to withstand a given voltage is specified in terms of clearance and creepage. A visual representation of the distinction between these terms and their applicability to board-mounted components is shown Figure 37.

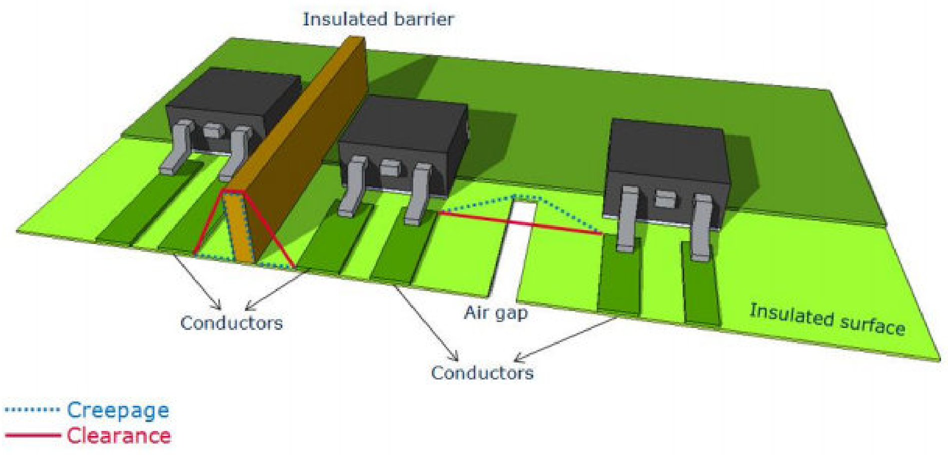


Figure 37. Definition of creepage and clearance (Brucchi & Peinhopf 2012.)

The creepage distance is defined as the shortest path between two conductive materials measured along the surface of an isolator, which is in between.

To determine the creepage distance the following parameters have to be considered:

- Working voltage

- Pollution degree
- Type of isolation
- Tracking resistance of isolation materials (CTI value)
- Circuit type (primary circuit, etc.).

It has to be noted that breakdown of the creepage distance is a slow phenomenon determined by DC or RMS voltage rather than peak events or transients. Inadequate creepage spacing may last for days, weeks or even months before they fail. (Brucchi & Peinhopf 2012.)

Clearance distance describes the shortest distance between two conductive materials measured through air. Breakdown along a clearance path is a fast phenomenon where damage can be caused by a very short duration impulse. Therefore, it is the maximum peak voltage including transients that is to be used to determine the required clearance spacing.

To determine the clearance distance the following parameters have to be considered:

- Working voltage
- Supply voltage
- Overvoltage category and allowable transients
- Pollution degree
- Type of isolation
- Installation altitude (Standards use 2000m as max. installation altitude)
- Periodical transients in primary circuits.

Clearances shall be dimensioned that overvoltage transients which may enter the equipment and peak voltages which may be generated within the equipment do not break down the clearance. A proper clearance and creepage distance between PCB traces is critical to avoid flashover or tracking between electrical conductors. Safety standards prescribe different spacing requirements depending on the voltage, application and other factors. (Brucchi & Peinhopf 2012.)

Besides safety standards, also IPC standards: *IPC- 2221 Generic Standard on Printed Board Design* and *IPC 9592 Performance Parameters for Power Conversion Devices* can be used as a guideline.

If there is no legal requirement to meet UL/EN standards distance recommendations (IPC standards above) can be used as a guideline. For example IPC-9592 standard for power conversion circuits provides linear functional spacing requirements: **creepage (mm) = 0.6+Vpeak×0.005.** However, where shortage of space on a PCB is an issue, a smaller spacing may be chosen, provided it still withstands the test voltage. (Brucchi & Peinhopf 2012.)

Device which is designed to be an environment where voltages with 1000V peaks can exists means minimum creepage distance of 0.6+1000x0.005 = 5.6 mm. Figure 38 represents two possibilities to solve spacing problem. If replacement of the components is not possible (on left side) the other possibility to increase artificially distance between components is to use high temperature silicone potting over component legs (right side). (Brucchi & Peinhopf 2012.)

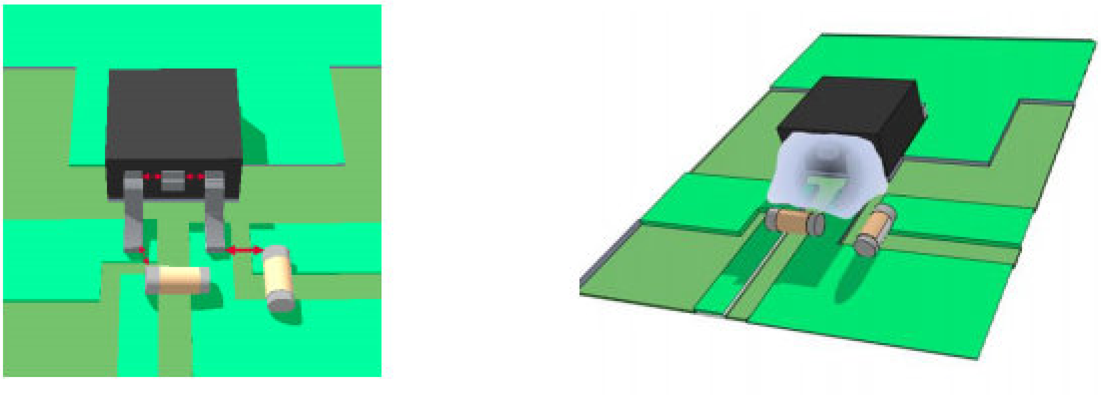
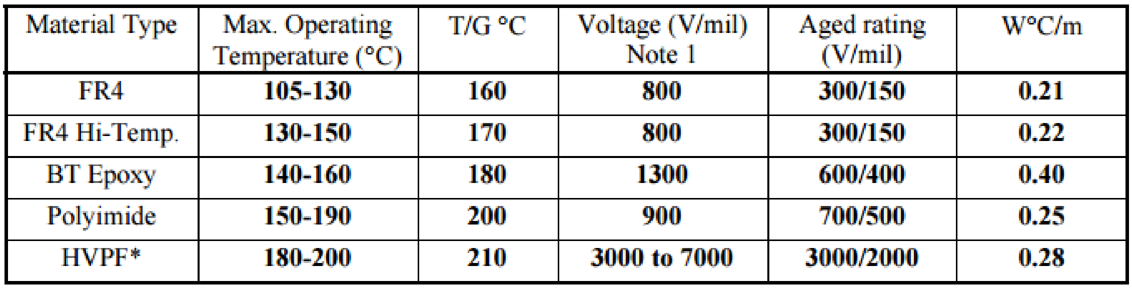


Figure 38. TO-263 soldered on PCB and very close to other two MELF resistors. (Brucchi & Peinhopf 2012.)

5.8 PCB Material Selection and Design Rules in HV System

The manufacturing process used in high voltage circuits is essentially the same steps as a normal printed circuit. There are however, differences in the material used and the properties of those materials. When a low voltage printed circuit (5 to 600 V) is designed and manufactured, it is more about spacing and circuit design than material. All printed circuit materials can support up to 1000 V. The medium voltage boards of typically 600 to 3000 V require greater care in selecting the base material and the subsequent processing as this voltage can easily support arcs and corona. The high voltage boards of 3000 V to a maximum limit of about 100 kV are limited to HVPF, Teflon and in some cases BT epoxy with serious effort and testing in areas of corona, field strengths and temperature control. (Tarzwell & Bahl 2004.)

Table 10 Materials that are supported with restrictions in HV PCB design (Tarzwell & Bahl 2004)



Material Type	Max. Operating Temperature (°C)	T/G °C	Voltage (V/mil) Note 1	Aged rating (V/mil)	W°C/m
FR4	**105-130**	**160**	**800**	**300/150**	**0.21**
FR4 Hi-Temp.	**130-150**	**170**	**800**	**300/150**	**0.22**
BT Epoxy	**140-160**	**180**	**1300**	**600/400**	**0.40**
Polyimide	**150-190**	**200**	**900**	**700/500**	**0.25**
HVPF*	**180-200**	**210**	**3000 to 7000**	**3000/2000**	**0.28**

Voltage ratings will decrease significantly from the effects of the high temperature, age, humidity and contamination from oils and chemicals. During one study of FR4 and the effects of aged voltage ratings it was noted that some manufacturers' samples de-rated from 750 V/mil to as low as 150 V/mil after as little as 6 months of exposure to the environment under an automobile hood. (Tarzwell & Bahl 2004.)

Practically, when designing PCB based on FR-4 material to 1000 V environment minimum of 6.7 mils thickness is needed. 1 mil is equivalent to 0.0254 mm which means only 0.17 mm thickness. This needs to take account when defining PCB stack-up. Thickness of the solder mask is usual between 0.75 to 1.5mils (20 to 40µm). Dielectric strength is 1000 V and drops to 500 V after aging 1000 h. In some cases it would be good idea to route high voltages on inner layers. Also doubled solder mask can be considered.
The shapes of the traces must be as round as possible to minimize corona effect. Any sharp 90^{o} bends needs to be avoided (Figure 39).

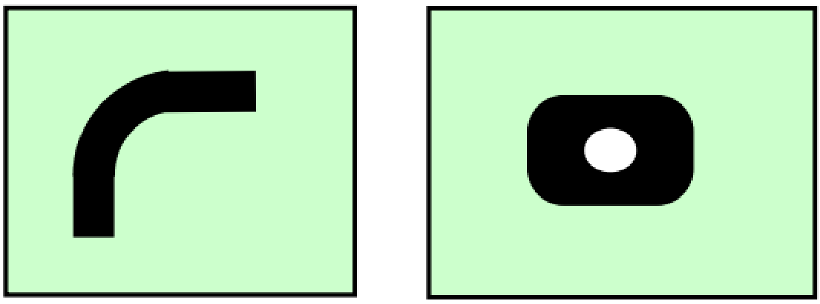


Figure 39. Rounded edges in traces and pads needs to be used in HV systems (Tarzwell & Bahl 2004)

The soldering should be round and ball like (Figure 40), avoiding sharp pointed tips that enhance the corona effect.

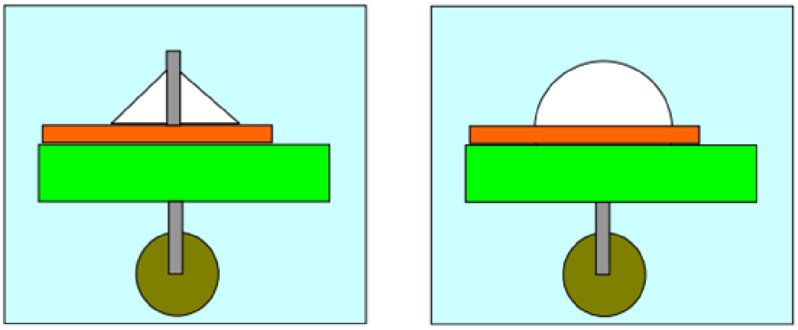


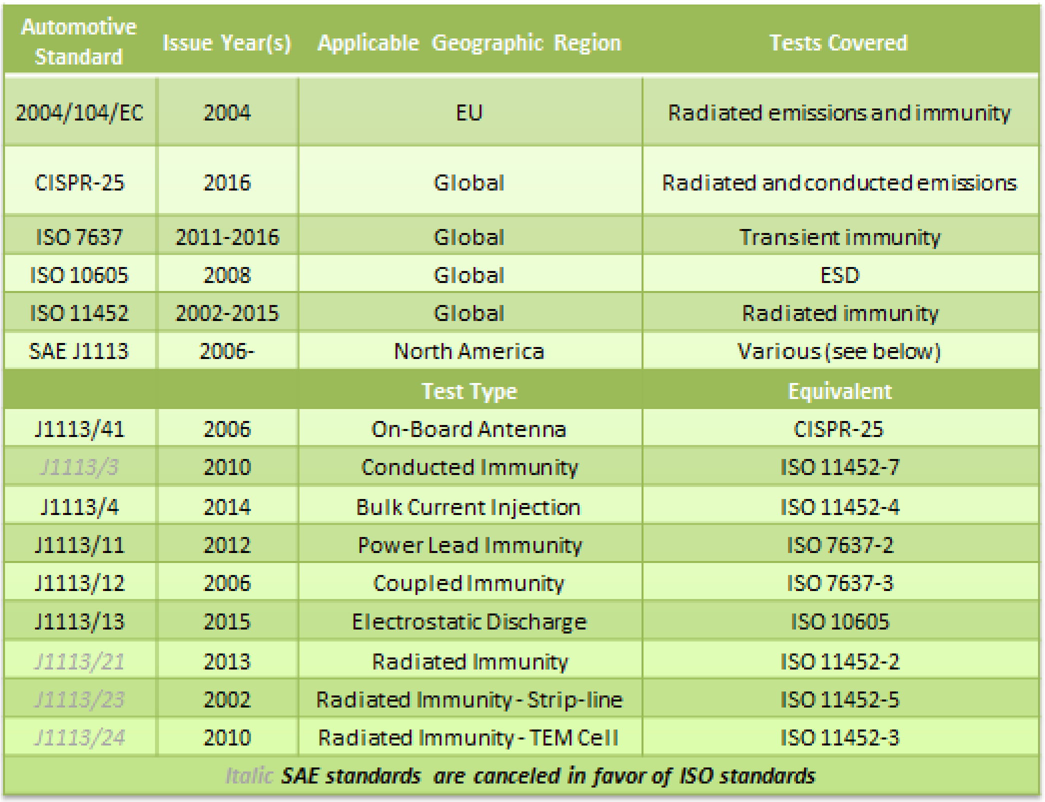
Figure 40. Traditional type of solder filet on left / HV type solder ball on right (Tarzwell & Bahl 2004)

For double-sided circuits, use as thick a board as you can, therefore giving you as much insulate material as possible between potentials. Place the high voltage circuits away from each other as much as physically possible. On multilayers, allow the manufacturer as much room between the layers as you can. One mistake with high voltage thick copper multilayers is the laminate does not press out fully without some air gaps and micro voids, which decrease the dielectric breakdown potential. On thicker copper multilayers, the common practice is to specify multiple layers of prepreg to lessen the chance of a continuous void between heavy copper layers. Use high resin content small glass bundle prepreg such as 2113 or 1080 in place of regular prepregs such as the thicker higher glass content 7268. (Tarzwell & Bahl 2004.)

5.9 EMC

Vehicle manufacturers have their own EMC requirements, which are based on standards referred in Table 11 International Automotive Standards for Component Testing. Typically, manufacturers define classes and/or limits given in standards which need to be fulfilled. There are different requirements in a vehicle and component level. Usually the component supplier is responsible that components fulfill EMC –requirements in a component level and vehicle manufacturer is responsible for the whole system.

Table 11 International Automotive Standards for Component Testing (O’Hara)



Automotive Standard	Issue Year(s)	Applicable Geographic Region	Tests Covered
2004/104/EC	2004	EU	Radiated emissions and immunity
CISPR-25	2016	Global	Radiated and conducted emissions
ISO 7637	2011-2016	Global	Transient immunity
ISO 10605	2008	Global	ESD
ISO 11452	2002-2015	Global	Radiated immunity
SAE J1113	2006-	North America	Various (see below)
		Test Type	**Equivalent**
J1113/41	2006	On-Board Antenna	CISPR-25
J1113/3	2010	Conducted Immunity	ISO 11452-7
J1113/4	2014	Bulk Current Injection	ISO 11452-4
J1113/11	2012	Power Lead Immunity	ISO 7637-2
J1113/12	2006	Coupled Immunity	ISO 7637-3
J1113/13	2015	Electrostatic Discharge	ISO 10605
J1113/21	2013	Radiated Immunity	ISO 11452-2
J1113/23	2002	Radiated Immunity - Strip-line	ISO 11452-5
J1113/24	2010	Radiated Immunity - TEM Cell	ISO 11452-3
Italic ***SAE standards are canceled in favor of ISO standards***			

In practice, EMC problems in HV systems can be prevented by using shielded cables, metallized connectors / shields around contacts and metallized covers. Shields are grounded to the vehicle chassis. It’s same time LV ground, but HV system protective earth is connected to the same point.

6 CONCLUSION

Low voltage systems are not disappearing totally from automotive industry, because human safety needs to be guaranteed also in the future. Devices consuming a great amount of energy (like the air conditioning system and power assisted steering) will most likely be implemented to 48V system (which still is low voltage) and eventually to the high voltage side. Control circuits will still remain in a low voltage side.

During this thesis, I succeeded to find answers to the most of questions I had before starting the investigations. As usual, deeper looking showed off that there is much knowledge available and it is impossible to gather everything inside the same covers. Interesting for me was electrical insulation requirements and how pollution degree and altitude affects to minimum creepage distances depending on used voltage. It is something not to worry about when designing low voltage products.

Human safety cannot be over-emphasized when speaking about high voltages. Orange color and required markings on wiring harnesses is a universal sign that caution is needed when touching the system. Together with proper grounding, active (e.g. HVIL) and passive (e.g. touch protection) safety systems creates basics for safe high voltage system.

Collected information makes it possible to answer customer requirements in the future from the design point-of-view. Still, there are many questions that need deeper research. For example, HV cables and connectors are different types than the LV variants. Some good topics for theses in the future would be: Coaxial cable processing, Pressure testing (IP-proof validation), High potential difference (hi-pot) testing and Semiconductors in HV systems. Most probably inside the company, activities are ongoing regarding those, but gathering everything together and sharing the information within the group would be a good idea.

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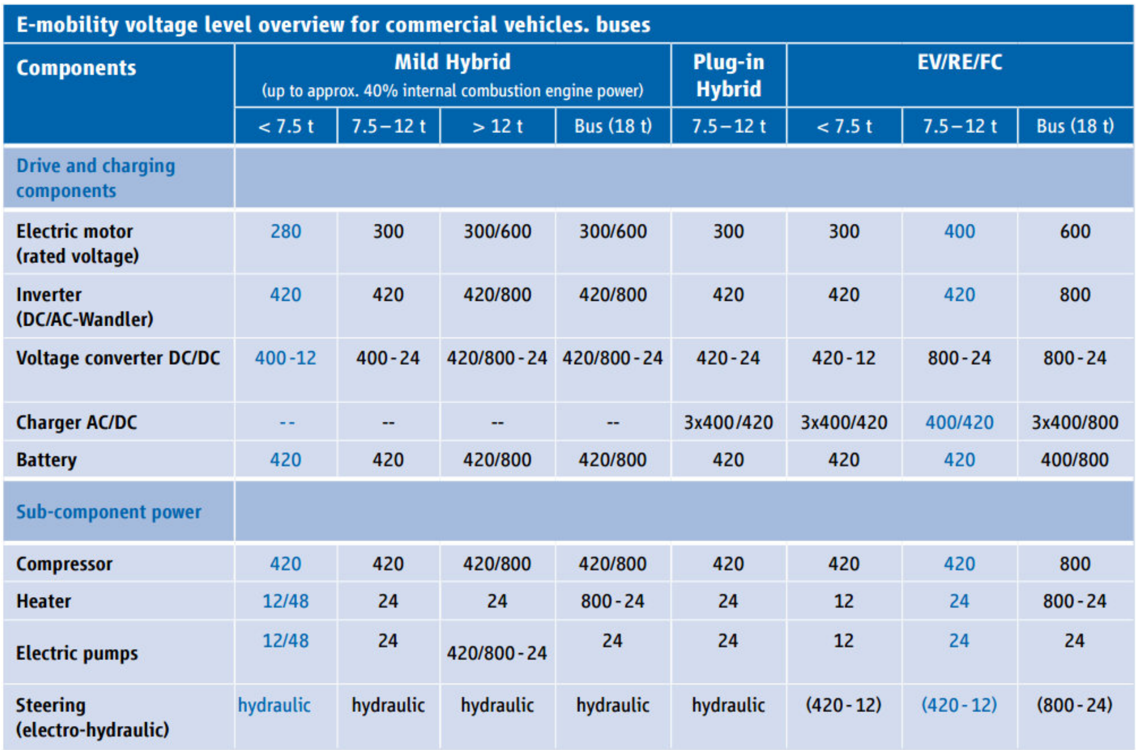
APPENDICES

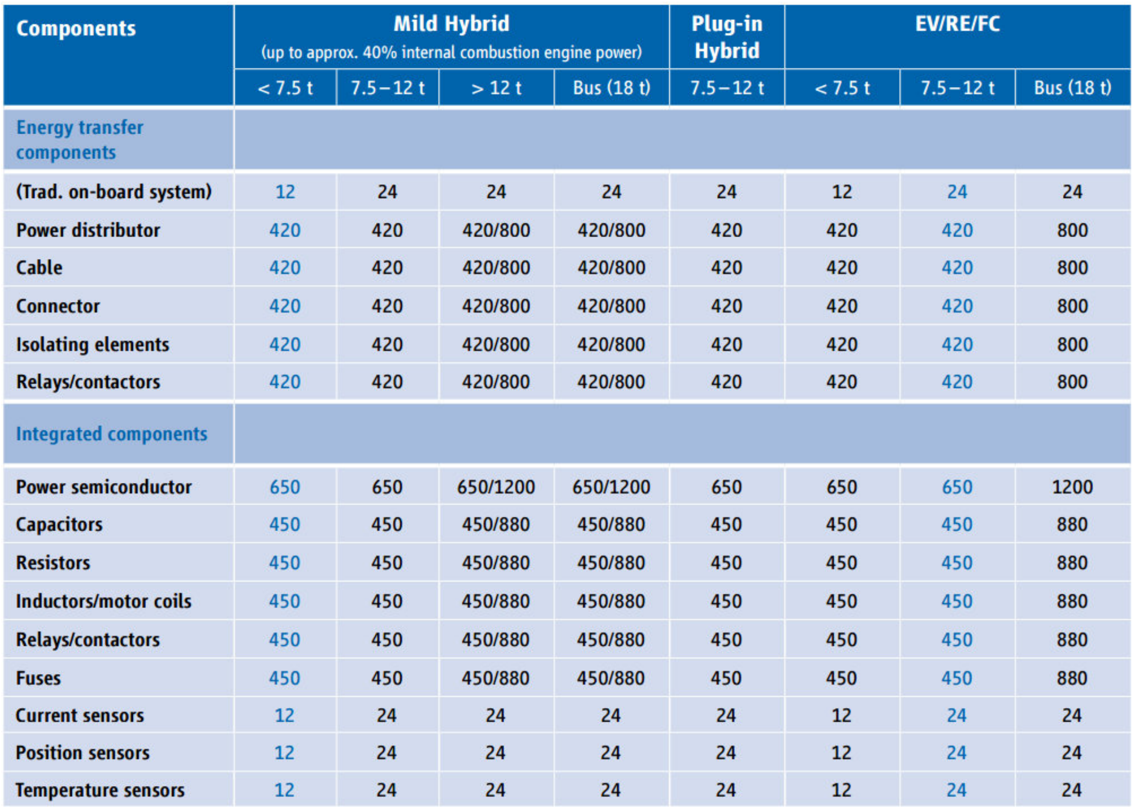
APPENDIX 1

Different voltage levels in commercial vehicle components according ZVEI 2013



E-mobility voltage level overview for commercial vehicles. buses

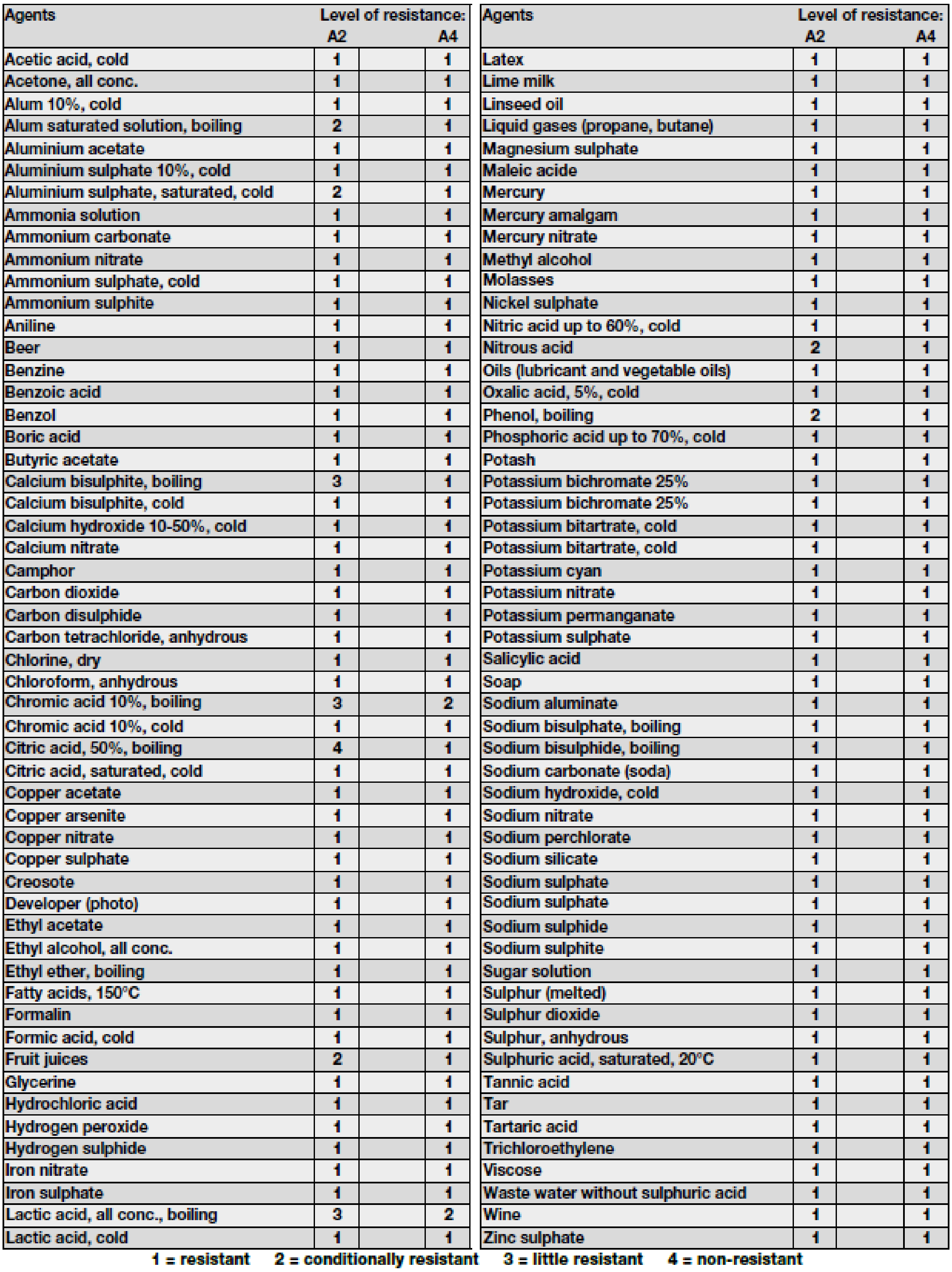
Components	Mild Hybrid (up to approx. 40% internal combustion engine power)				Plug-in Hybrid	EV/RE/FC		
	< 7.5 t	7.5 – 12 t	> 12 t	Bus (18 t)	7.5 – 12 t	< 7.5 t	7.5 – 12 t	Bus (18 t)
Drive and charging components								
Electric motor (rated voltage)	280	300	300/600	300/600	300	300	400	600
Inverter (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)



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

APPENDIX 2

Chemical resistance of stainless steel (A2 / A4) enclosure materials (Rolec)



Agents	Level of resistance: A2	A4	Agents	Level of resistance: A2	A4
Acetic acid, cold	1	1	Latex	1	1
Acetone, all conc.	1	1	Lime milk	1	1
Alum 10%, cold	1	1	Linseed oil	1	1
Alum saturated solution, boiling	2	1	Liquid gases (propane, butane)	1	1
Aluminium acetate	1	1	Magnesium sulphate	1	1
Aluminium sulphate 10%, cold	1	1	Maleic acide	1	1
Aluminium sulphate, saturated, cold	2	1	Mercury	1	1
Ammonia solution	1	1	Mercury amalgam	1	1
Ammonium carbonate	1	1	Mercury nitrate	1	1
Ammonium nitrate	1	1	Methyl alcohol	1	1
Ammonium sulphate, cold	1	1	Molasses	1	1
Ammonium sulphite	1	1	Nickel sulphate	1	1
Aniline	1	1	Nitric acid up to 60%, cold	1	1
Beer	1	1	Nitrous acid	2	1
Benzine	1	1	Oils (lubricant and vegetable oils)	1	1
Benzoic acid	1	1	Oxalic acid, 5%, cold	1	1
Benzol	1	1	Phenol, boiling	2	1
Boric acid	1	1	Phosphoric acid up to 70%, cold	1	1
Butyric acetate	1	1	Potash	1	1
Calcium bisulphite, boiling	3	1	Potassium bichromate 25%	1	1
Calcium bisulphite, cold	1	1	Potassium bichromate 25%	1	1
Calcium hydroxide 10-50%, cold	1	1	Potassium bitartrate, cold	1	1
Calcium nitrate	1	1	Potassium bitartrate, cold	1	1
Camphor	1	1	Potassium cyan	1	1
Carbon dioxide	1	1	Potassium nitrate	1	1
Carbon disulphide	1	1	Potassium permanganate	1	1
Carbon tetrachloride, anhydrous	1	1	Potassium sulphate	1	1
Chlorine, dry	1	1	Salicylic acid	1	1
Chloroform, anhydrous	1	1	Soap	1	1
Chromic acid 10%, boiling	3	2	Sodium aluminate	1	1
Chromic acid 10%, cold	1	1	Sodium bisulphate, boiling	1	1
Citric acid, 50%, boiling	4	1	Sodium bisulphide, boiling	1	1
Citric acid, saturated, cold	1	1	Sodium carbonate (soda)	1	1
Copper acetate	1	1	Sodium hydroxide, cold	1	1
Copper arsenite	1	1	Sodium nitrate	1	1
Copper nitrate	1	1	Sodium perchlorate	1	1
Copper sulphate	1	1	Sodium silicate	1	1
Creosote	1	1	Sodium sulphate	1	1
Developer (photo)	1	1	Sodium sulphate	1	1
Ethyl acetate	1	1	Sodium sulphide	1	1
Ethyl alcohol, all conc.	1	1	Sodium sulphite	1	1
Ethyl ether, boiling	1	1	Sugar solution	1	1
Fatty acids, 150°C	1	1	Sulphur (melted)	1	1
Formalin	1	1	Sulphur dioxide	1	1
Formic acid, cold	1	1	Sulphur, anhydrous	1	1
Fruit juices	2	1	Sulphuric acid, saturated, 20°C	1	1
Glycerine	1	1	Tannic acid	1	1
Hydrochloric acid	1	1	Tar	1	1
Hydrogen peroxide	1	1	Tartaric acid	1	1
Hydrogen sulphide	1	1	Trichloroethylene	1	1
Iron nitrate	1	1	Viscose	1	1
Iron sulphate	1	1	Waste water without sulphuric acid	1	1
Lactic acid, all conc., boiling	3	2	Wine	1	1
Lactic acid, cold	1	1	Zinc sulphate	1	1

1 = resistant 2 = conditionally resistant 3 = little resistant 4 = non-resistant

APPENDIX 3 1(3)

Electrically propelled vehicles - Standardization

IEC 62752:2016
In-Cable Control and Protection Device for mode 2 charging of electric road vehicles (IC-CPD)

ISO 12405-1:2011
Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 1: High-power applications

ISO 12405-2:2012
Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 2: High-energy applications

ISO 12405-3:2014
Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 3: Safety performance requirements

ISO 17409:2015
Electrically propelled road vehicles -- Connection to an external electric power supply -- Safety requirements

ISO 18300:2016
Electrically propelled vehicles -- Test specifications for lithium-ion battery systems combined with lead acid battery or capacitor

ISO 23273:2013
Fuel cell road vehicles -- Safety specifications -- Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen

ISO 23274-1:2013
Hybrid-electric road vehicles -- Exhaust emissions and fuel consumption measurements -- Part 1: Non-externally chargeable vehicles

ISO 23274-2:2012
Hybrid-electric road vehicles -- Exhaust emissions and fuel consumption measurements -- Part 2: Externally chargeable vehicles

ISO 23828:2013
Fuel cell road vehicles -- Energy consumption measurement -- Vehicles fuelled with compressed hydrogen

ISO 6469-1:2009
Electrically propelled road vehicles -- Safety specifications -- Part 1: On-board rechargeable energy storage system (RESS)

ISO 6469-2:2009

APPENDIX 3 2(3)

Electrically propelled road vehicles -- Safety specifications -- Part 2: Vehicle operational safety means and protection against failures

ISO 6469-3:2011
Electrically propelled road vehicles -- Safety specifications -- Part 3: Protection of persons against electric shock

ISO 6469-4:2015
Electrically propelled road vehicles -- Safety specifications -- Part 4: Post crash electrical safety

ISO 8714:2002
Electric road vehicles -- Reference energy consumption and range -- Test procedures for passenger cars and light commercial vehicles

ISO 8715:2001
Electric road vehicles -- Road operating characteristics

ISO/AWI 20762 [Under development]
Electrically propelled road vehicles -- Determination of power for propulsion of hybrid electric vehicle

ISO/AWI 21498 [Under development]
Electrically propelled road vehicles -- Electrical tests for voltage class B components

ISO/AWI 21782-1 [Under development]
Electrically propelled road vehicles -- Test specification for components for electric propulsion -- Part 1: General

ISO/AWI 21782-2 [Under development]
Electrically propelled road vehicles -- Test specification for components for electric propulsion -- Part 2: Testing performance of systems

ISO/AWI 21782-3 [Under development]
Electrically propelled road vehicles -- Test specification for components for electric propulsion -- Part 3: Testing performance of motor and inverter

ISO/AWI 21782-6 [Under development]
Electrically propelled road vehicles -- Test specification for components for electric propulsion -- Part 6: Testing reliability of motor and inverter

ISO/DIS 12405-4 [Under development]
Electrically propelled road vehicles --Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing

ISO/DIS 6469-2 [Under development]

APPENDIX 3 3(3)

Electrically propelled road vehicles -- Safety specifications element -- Part 2: Vehicle operational safety

ISO/DIS 6469-3 [Under development]
Electrically propelled road vehicles -- Safety specifications -- Part 3: Protection of persons against electric shock

ISO/NP 12405-3 [Under development]
Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 3: Safety performance requirements

ISO/NP 6469-1 [Under development]
Electrically propelled road vehicles -- Safety specifications -- Part 1: On-board rechargeable energy storage system (RESS)

ISO/NP TR 8713 [Under development]
Electrically propelled road vehicles -- Vocabulary

ISO/PAS 16898:2012
Electrically propelled road vehicles -- Dimensions and designation of secondary lithium-ion cells

ISO/PAS 19295:2016
Electrically propelled road vehicles -- Specification of voltage sub-classes for voltage class B

ISO/PAS 19363:2017
Electrically propelled road vehicles -- Magnetic field wireless power transfer -- Safety and interoperability requirements

ISO/TR 11954:2008
Fuel cell road vehicles -- Maximum speed measurement

ISO/TR 11955:2008
Hybrid-electric road vehicles -- Guidelines for charge balance measurement

ISO/TR 8713:2012
Electrically propelled road vehicles -- Vocabulary

APPENDIX 4

Pin configuration of CHAdeMO and COMBO 1&2 connectors.

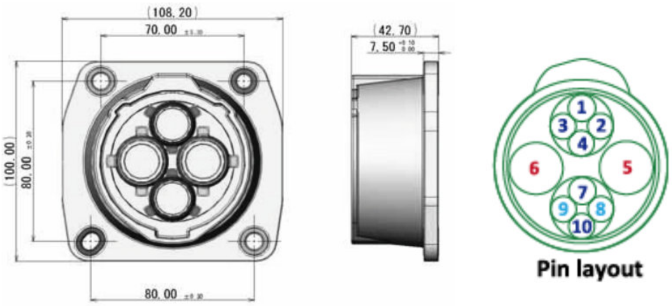


Figure 41 CHAdeMO connector dimension and pin configuration (IA-HEV)

Table 12 CHAdeMO connector pin specification (IA-HEV)

Pin nº	Colour	mm²	Name of the pin
1	Black	0.75	Ground
2	Green	0.75	Start/ stop charging
3	White		None
4	Brown	0.75	Permission/ Prohibition charging
5	Black	22 o 40	Energy supply negative
6	White	22 o 40	Energy supply positive
7	Blue	0.75	Verification of the connector connection
8	Orange	0.75	CAN-H
9	Red	0.75	CAN-L
10	Pink	0.75	Start/ stop charging 2

Pin configuration of COMBO connectors 1 & 2 are described on Table 13 and Table 14

Table 13 COMBO 1 pin configuration (IA-HEV)

	Inlet	Function	Comments
			
	PP	Communications/charging process control	Proximity inlet
	CP		Control pilot
	PE	Earth ground	EV to earth ground
	N/L2	AC 1-phase charging	Neutral / Phase 2
	L1		Phase 1
	DC -	DC charging	DC negative inlet
	DC +		DC positive inlet

Table 14 COMBO 2 pin configuration (IA-HEV)

	Inlet	Function		Comments
				
	PP	Communications/charging process control		Proximity inlet
	CP			Control pilot
	PE	Earth ground		EV to earth ground
	N	AC 3-phase charging	AC 1-phase charging	Neutral
	L1			Phase 1
	L2		-	Phase 2
	L3		-	Phase 3
	DC -	DC charging		DC negative inlet
	DC +			DC positive inlet