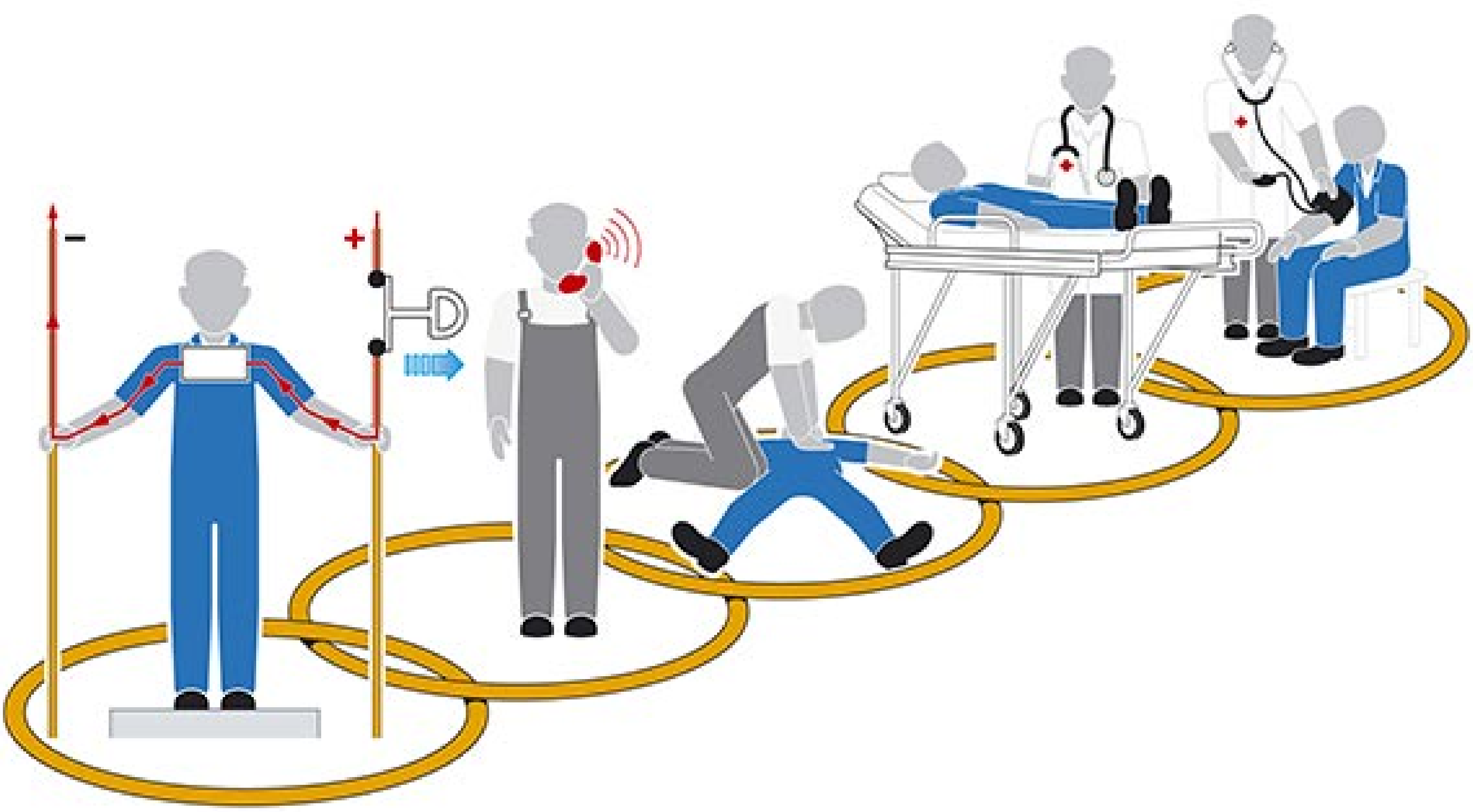
Reference Manual

HIGH-VOLTAGE SAFE WORKING PRACTICES



Technical Training

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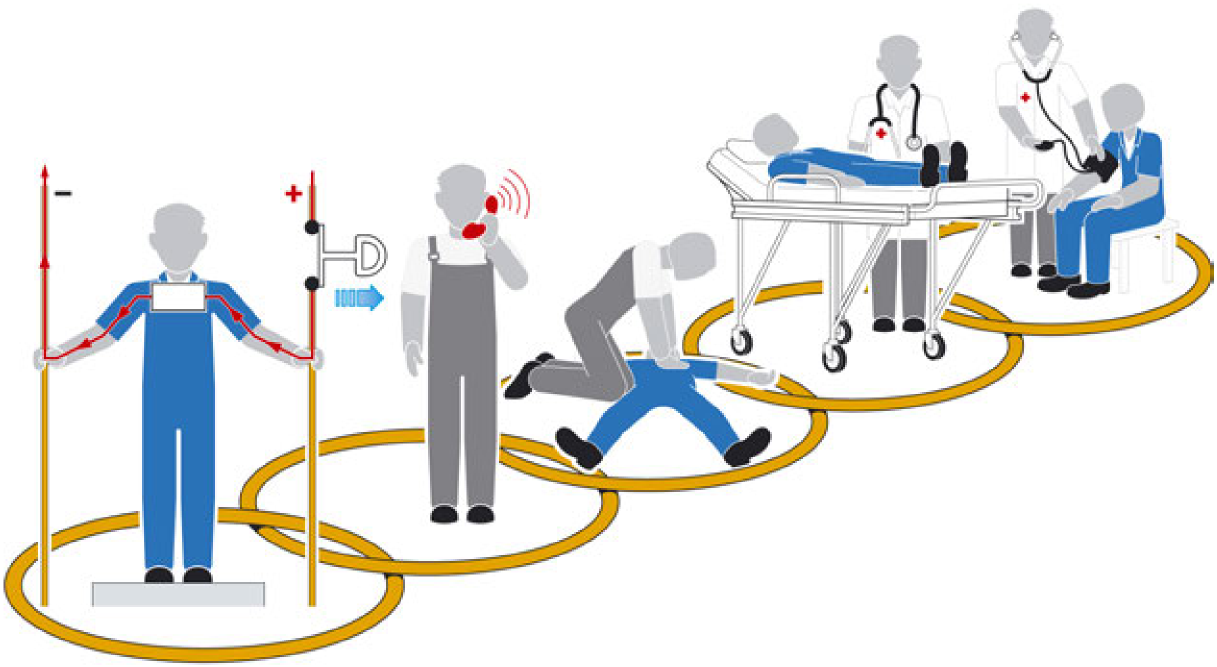
High-voltage Safe Working Practices



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BMW Service

General information

Symbols used

The following symbol is used in this document to facilitate better comprehension or to draw attention to very important information:

Contains important safety information and information that needs to be observed strictly in order to guarantee the smooth operation of the system.

Information status and national-market versions

BMW Group vehicles meet the requirements of the highest safety and quality standards. Changes in requirements for environmental protection, customer benefits and design render necessary continuous development of systems and components. Consequently, there may be discrepancies between the contents of this document and the vehicles available in the training course.

This document basically relates to the European version of left hand drive vehicles. Some operating elements or components are arranged differently in right-hand drive vehicles than shown in the graphics in this document. Further differences may arise as the result of the equipment specification in specific markets or countries.

Additional sources of information

Further information on the individual topics can be found in the following:

- Owner's Handbook
- Integrated Service Technical Application.

Contact: conceptinfo@bmw.de

The information contained in this document forms an integral part of the BMW Group Technical Qualification and is intended for the trainer and participants in the seminar. Refer to the latest relevant information systems of the BMW Group for any changes/additions to the technical data.

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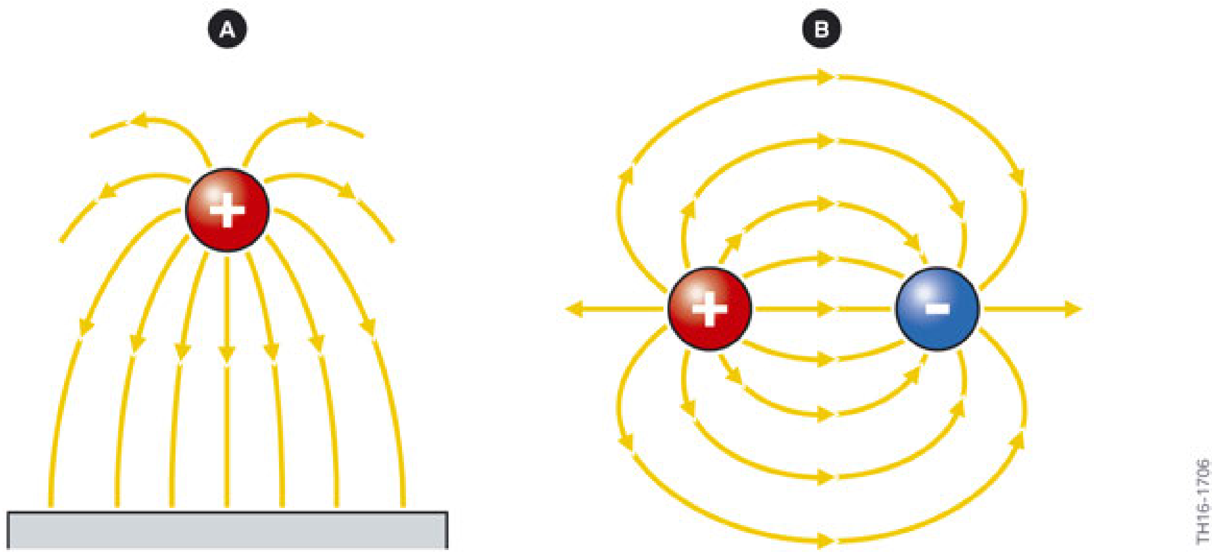
1. Safe Working Practices

1.1. Basic physical effects

1.1.1. High electrical voltage

Electrical field

Each electrically charged body is surrounded by an electrical field. This effect is known for example from non-conducting bodies when they are charged electrostatically. The reason for the electrical field is a potential difference between the electrically charged body and other bodies in its environment. One can also use the term "electrical voltage" instead of the term "potential difference".



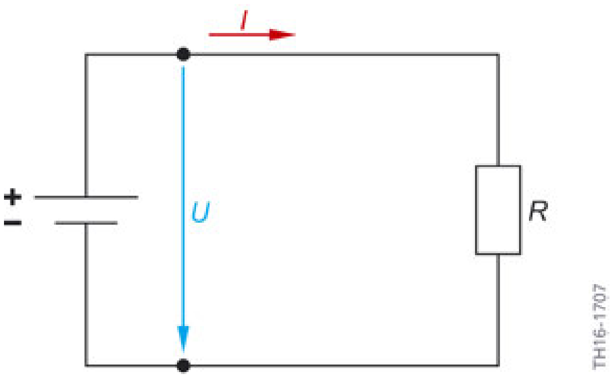
Electrical fields of charged bodies

Index	Explanation
A	Electrical field of a positively charged sphere
B	Electrical field of a positively charged sphere and a negatively charged sphere

Live electrical conductors also generate an electrical field in their surrounding area. The electrical voltages used in high-voltage vehicles are in a range above 100 V. The resulting field thus poses no direct danger. The electrical field of electrostatically charged bodies can be considerably stronger in comparison. For example if one approaches a live high-voltage cable with his/her hand, one cannot expect to cause a spark discharge.

Electrical voltage as a cause for current flow

The electrical voltage is not only a cause for the electrical field in the environment of bodies, but also for the current flow in the circuit. The higher the voltage (U), the greater the current level (I) for a specified electrical resistance (R). In the high-voltage electrical system of high-voltage vehicles, the voltages used are much higher than those in the known 12 V vehicle electrical system.



Single circuit

Example: R = 1 kΩ

Voltage (U)	Current level (I)
12 V	12 mA
120 V	120 mA
360 V	360 mA

Naturally the technical components in the high-voltage vehicle electrical system are designed for the higher voltage so that the desired current level is obtained. The resistance of the human body is independent of the applied electrical voltage. Therefore a significantly higher current flows through the human body if a person makes contact with live parts in the high-voltage electrical system (in comparison to the 12 V vehicle electrical system). The effect of the electrical current on the human body is described in the chapter "Dangers posed by electricity".

1.1.2. High electrical current

Current-carrying conductors are surrounded by a magnetic field. The higher the current level in the conductor, the stronger the magnetic field.

The interaction between magnetic field and electric circuit (force action, induction) has already been described in the chapter “Electrical machines – Important terms and physical laws": If a current-carrying conductor is located in a magnetic field, the Lorentz force will act on its internal moving charge carriers. If an electric conductor is moved inside a magnetic field, a voltage will be induced in it.

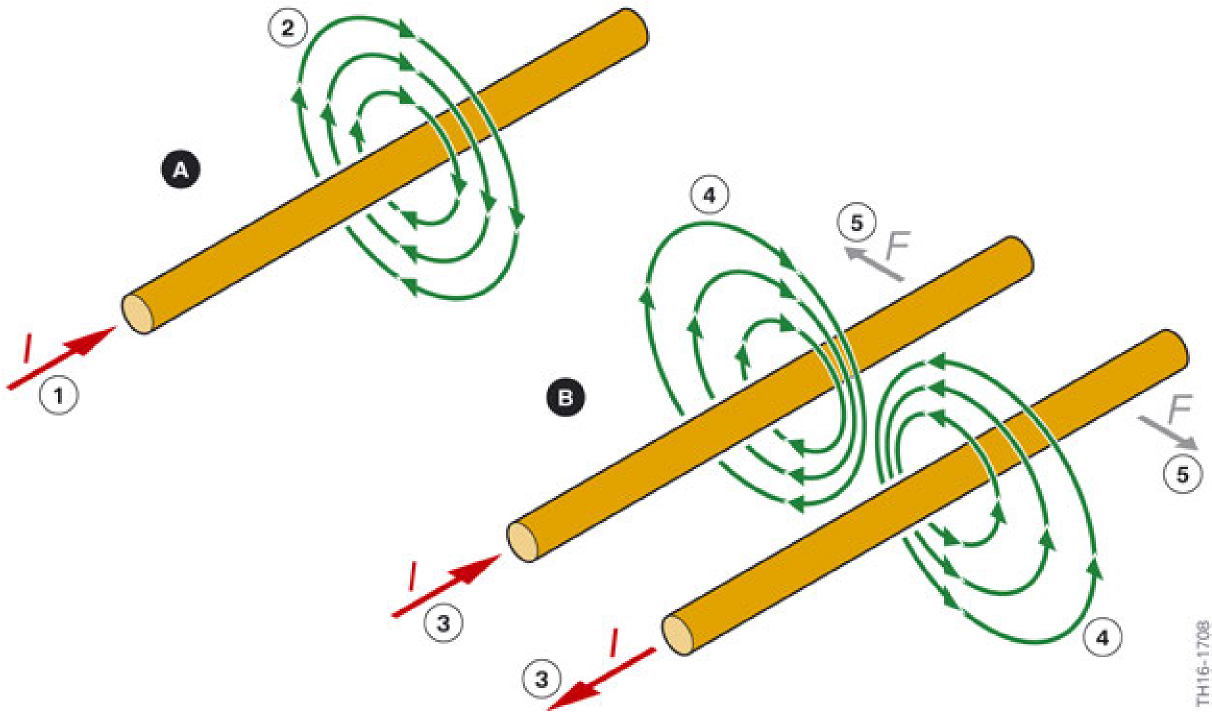
If two current-carrying conductors are located beside each other, then these two effects can be observed here also:

1 Force

2 Induction

Force

The magnetic fields of two current-carrying conductors overlap with each other. In the high-voltage electrical system there are parallel lines from/to the high-voltage battery (positive and negative lead). The current flows in the opposite direction in these lines. The magnetic fields of two lines overlap with each other so that the field lines become thicker between the lines. The magnetic field is thus stronger there.



Magnetic field of current-carrying conductors

Index	Explanation
A	Single current-carrying conductor
B	2 parallel current-carrying conductors
1	Current flows in one direction
2	Magnetic field caused by the flowing current
3	Two currents in opposite direction
4	Magnetic field caused by the two flowing currents
5	Force on the two conductors as a result of the magnetic field

According to the law of conservation of energy the effect of the overlap must counteract its cause (i.e. the current flow). For this reason a force is exerted in the direction on both conductors so that the reinforcement of the magnetic field is counteracted and the lines are therefore pressed apart.

Example: Current level in both conductors I = 200 A, distance of conductor r = 2 cm, length of conductor l = 1 m. Force on both conductors F = 0.4 N. By comparison: The weight force of a bar of a chocolate (m = 102 g) is approx. 1.0 N.

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The selected numerical values can occur in a high-voltage vehicle. The size of the force on the conductor is relatively small due to the magnetic field. However, it is important to observe the following during the installation of high-voltage cables.

⚠

Carefully insert or clip the high-voltage cables into the provided mounting clips.

Use available strain relief devices for high-voltage cables.

Secure the screw connections of high-voltage cables with the specified tightening torque. Safely close locks at plug connections of high-voltage cables.

Observe the specified distances between individual high-voltage cables and between high-voltage cables and signal lines, for example.

When driving, the currents which occur are not just constant currents. Instead, above all (superimposed) alternating currents occur. This means that the forces on the lines are also not constant, but change their direction according to the current direction. The mountings or connections must therefore prevent the high-voltage cables from "vibrating loose" due to the alternating forces. If this is not observed during service work, noise may occur due to the vibrations. It is also conceivable that an electrical connection will come undone, resulting in an inadmissibly high contact resistance.

Induction

If the current level in a conductor changes, then the magnetic field in its environment also changes. A voltage is induced in the conductor itself which is important mainly for wound conductors (coils).
If other electric conductive bodies are in the magnetic field of the conductor, a voltage is also induced therein. This ultimately leads to a current flow. The larger the change in current and faster the rate of change, the higher the induced voltage. As high current levels and switching frequencies are used in the high-voltage electrical system of high-voltage vehicles, the induction effect is important. There is no risk for service employees. However, the conditions for ensuring the electromagnetic compatibility (EMC) must be taken into consideration when laying signal lines near high-voltage cables.

1.1.3. High frequency

Inverters and DC/DC converters are used in the high-voltage vehicle electrical systems. These power electronics circuits operate with high switching frequencies. The voltage and current characteristics of the high-voltage cables are therefore not constant, but have frequencies of up to several 100 kHz. The electrical and magnetic fields generated as a result can cause interference voltages and interference currents in neighbouring lines. These effects have been known since the introduction of electronic circuits. These effects due to inductances and capacitances in and between the lines can be shown in a wiring diagram.

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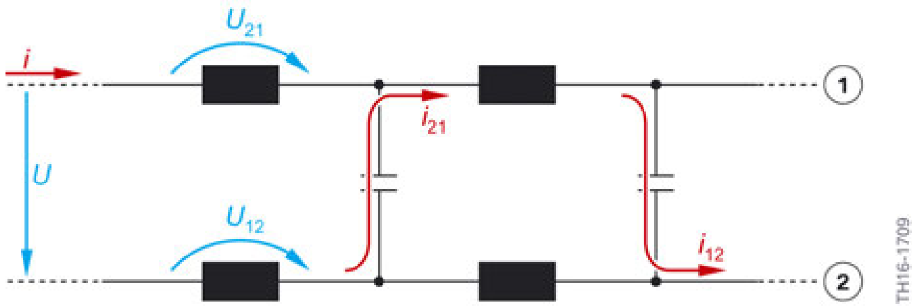
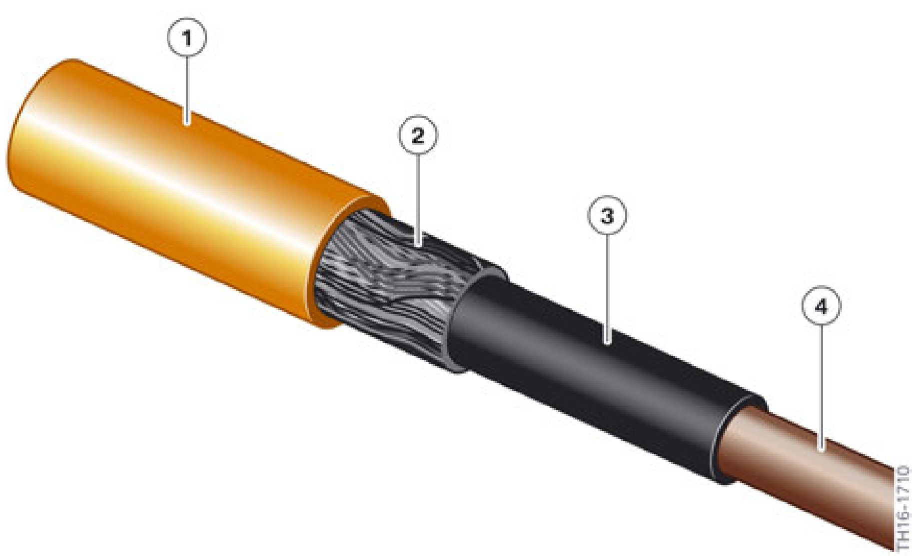


Inductance and capacitance of two parallel lines

Index	Explanation
1	Line 1
2	Line 2
U_{12}	Interference voltage produced in line 2 due to inductive coupling, caused by the current in line 1
U_{21}	Interference voltage produced in line 1 due to inductive coupling, caused by the current in line 2
i_{12}	Interference current produced in line 2 due to capacitive coupling, caused by the voltage in line 1
i_{21}	Interference current produced in line 1 due to capacitive coupling, caused by the voltage in line 2

To minimize the interference on signal lines, corresponding counter-measures can be taken, e.g. use of shielded or twisted lines or ensuring the largest possible distance between the lines. These measures are combined under the term "electromagnetic compatibility".

In high-voltage vehicles, such interference voltages and currents occur in particular in the vicinity of high-voltage cables. The high-voltage cables are shielded in order to ensure electromagnetic compatibility.



Shielded high-voltage cable

Index	Explanation
1	Outer protective sleeve in the warning color orange
2	Wire braiding as shield
3	Insulation of the electric conductor
4	Electrical conductor

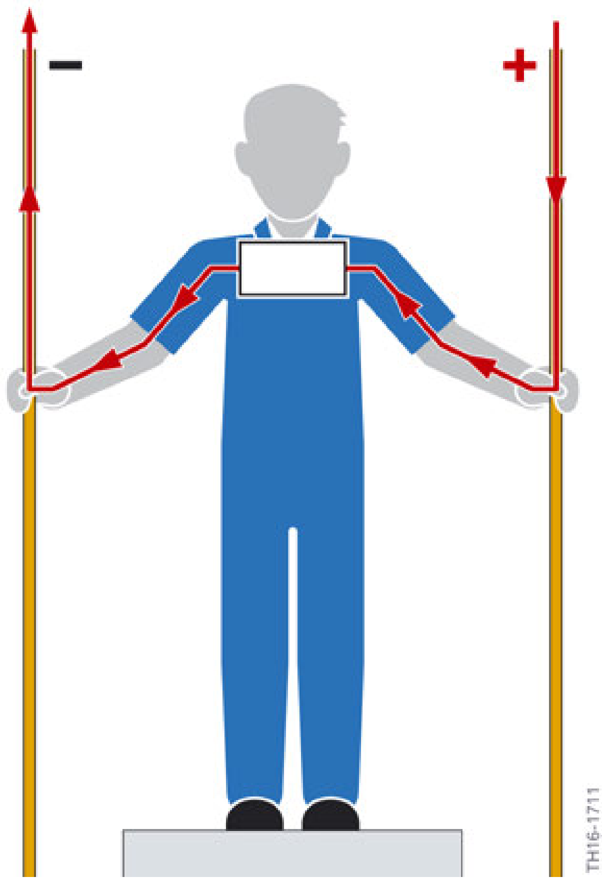
All electromagnetic compatibility measures implemented in the vehicle must not be impaired by incorrectly performed repairs or makeshift solutions. Otherwise, malfunctions must be expected in the complex electronic systems in the vehicle. In high-voltage vehicles this also applies to the structural design of the high-voltage components such as the high-voltage cables or power electronics. Damage to the insulation or housing parts must therefore not be repaired in a makeshift way. This can otherwise result in danger for the vehicle users and service employees as well as in functional impairment due to interference voltages and currents.

1.2. Dangers posed by electricity

1.2.1. Current flow through the human body

Influencing factors

The cells of the human body are electrically conductive to a limited extent. The high liquid content in the cells is one of the main causes of this. If a person touches live components, an electrical current may flow through his body. The current flows through the body via the shortest route. Different organs may be affected depending on the route covered in the body. The respiratory organs and the heart are also included in the following graphic.



Example of a current flow through the human body

Resistance values can also be specified for different routes covered by the current in the human body. How big the ohmic resistance of the human body is depends on the following influencing factors.

- Clothes
- Moisture content of the skin
- Length and type of route in the body

The thicker and dryer the clothing items on the bodies are, at which the electrical current enters and exits the body, the larger the resistance value. If the skin is wet with water or sweat, the electrical resistance of the body decreases. If the current in the body covers a short route, the resistance is less than when the current covers a longer route. The following table provides reference values for the electrical resistance of the human body which can arise due to the above-mentioned influencing factors.

Route of the electrical current in the body	Ohmic resistance (approximate value)
From one hand to another hand	Approx. 1000 Ω
From one hand to both feet	Approx. 750 Ω
From both hands to both feet	Approx. 500 Ω
From both hands to the torso	Approx. 250 Ω

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The current level is only dependent on the voltage applied and the ohmic resistance of the body:
I = U : R.

Examples:

Situation	Voltage applied (U)	Resistance (R) of the body	Current level (I) in the body
Person touches a terminal of a 12 V battery with each hand	12 V	1000 Ω	12 mA
Person touches a terminal of a high-voltage battery with each hand	420 V	1000 Ω	420 mA
Person touches the phase conductor of a wall socket with one hand and stands with both feet on the ground	230 V	750 Ω	307 mA

Effects of the electrical current in the human body

The electrical current not only has technical effects (heat effect, light effect, chemical and magnetic effect). Through an electrical current effects also arise on the bodies of living things, i.e. also on the human body. Here one talks about a physiological effect.

The reason for this is that many functions in the human body are controlled by electrical processes. The control of muscular movement is effected by electrical pulses which also include the heartbeat. The information of the sensory organs is also transported electrically via nerves to the brain. And the brain also works with electrical signals. These signals in the human body have much lower voltages (mV) and current levels (µA).

If an electrical current flows through the human body which is generated by an external voltage source, this is superposed with the natural electrical signals. The natural electrical control processes may be severely disrupted as a result. One feels an electric shock at least and twitches.

In the case of larger current levels one may no longer be able to control the muscle movements. This can have the effect that a person is no longer able to release the live part. A dangerous circuit closes when this so-called "let go threshold" is exceeded: The longer the electrical current flows through the human body, the more harmful its effects are.

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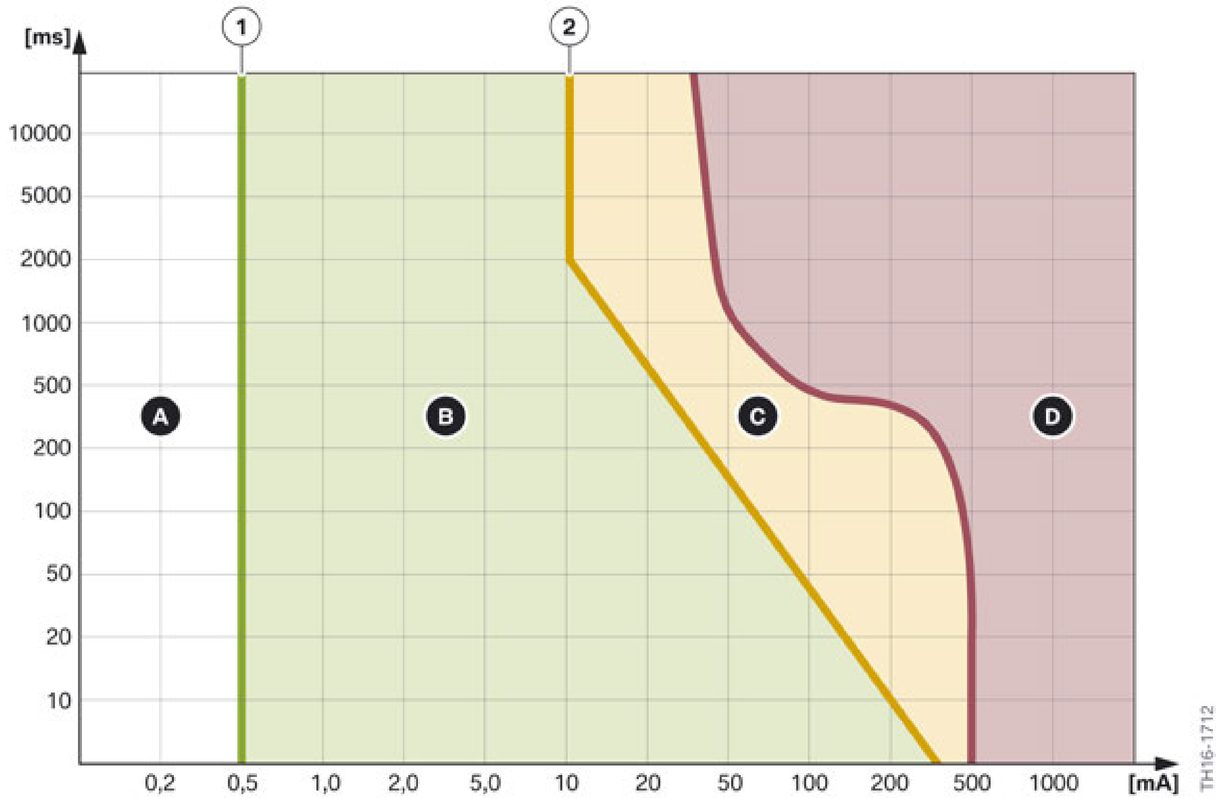


Effects of electrical current in the human body dependent on duration of exposure and current level. Source: VDE 0100, Part 410

Index	Explanation
A	Non-perceptible effect
B	Perceptible effect, to the point of muscle cramps
C	Muscle cramps, difficulties breathing
D	Ventricular fibrillation, respiratory failure, heart failure
1	Perception threshold
2	Release limit

The most dangerous failure of the muscle movement concerns the respiratory muscles and the heart muscle. Breathing can stop as a result. Depending on the current level, the duration of the current flow and the frequency (alternating current) it may cause ventricular fibrillation. Ventricular fibrillation is understood as small, high frequency movements of the heart muscle which cannot sustain the bloodstream.

⚠

Both for respiratory failure and also for ventricular fibrillation, circulation and thus the oxygen supply of the entire body come to a standstill. There is an acute danger to life! In such cases first -aid measures must be performed straight away to save the health and life of the respective person.

In addition, the heat effect of the electrical current can cause damage in the human body. It may lead to external burns which are primarily triggered by an electric arc. The electrical current inside the body heats the tissue through which it flows. The body fluids in particular are heated so strongly by the electrical current flow that they evaporate. One talks about electro-coagulation in this case. This causes the organs to lose their operability within a short space of time and circulation also comes to a standstill. There is an acute danger to life!

In addition to these direct and immediate effects of the electrical current, there are also those which appear after some time. Life-threatening situations can still arise. For example destroyed cells in the body are slowly degraded by an electrical accident. This process can last up to several days.

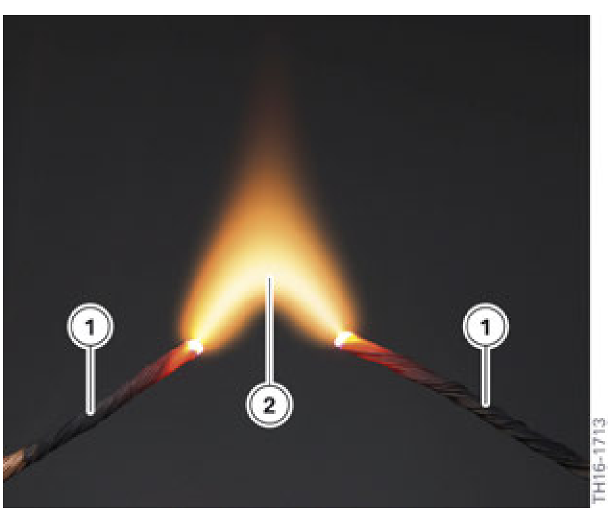
Substances which have to be processed by the kidneys build up. If there is a large number of destroyed cells, the kidneys become overloaded, which may result in renal failure. For this reason, it is important particularly for electrical accidents that further medical examinations are undertaken after the first-aid measures.

1.2.2. Electric arc

Definition

An electric arc is a current flow between two conductors over a line made up of gas (e.g. air). This gas line is normally insulating. An electric arc can occur if two conductors make contact and then a current flows. If the two conductors are then separated from each other, a very small gap arises between these conductors for a moment. A very high electrical field strength, which can be in the gap over the breakdown field strength of the gas, arises through the small gap. It can result in a breakdown in this case, whereby gas molecules are ionized.

Ions and electrons are also torn out from the material of the two conductors so that the material is consumed as a result. Another result is that mobile charge carriers arise: positively charged ions and negatively charged electrons. Based on the voltage applied these move in the gap to the conductors. They react there with the conductors. Mobile charge carriers mean that an electrical current flows. This type of occurrence of a current flow in gases is called gas discharge. In the case of an electric arc it is a continuous process. More and more new charge carriers are being generated and the current flow remains. A so-called plasma forms between the conductors.



Electric arc between 2 conductors

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Index	Explanation
1	Conductor
2	Electric arc

A prerequisite for the occurrence of an electric arc is minimum voltage and minimum current level (before the conductors are separated). There are no general values but these are dependent on the material of the conductor.

Electric arcs were used in the past in lamps as a light source. Today they are primarily used for research purposes and for welding (Wolfram inert gas welding).

Effects and dangers

The mobile charge carriers meet in the plasma between the two conductors, whereby the gas heats up. Depending on the material of the conductor and the ambient gas, temperatures of approx. 4000° C (7232° F) and higher may arise. Additional mobile charge carriers may arise from the conductor material as a result of this extremely high temperature. This can cause the electric arc to "burn" continuously and the conductor material is consumed permanently.

The material consumption is a technical effect: If an electric arc arises at open switching contacts, this can cause wear at the contacts. For this reason the function of many relays or switch contactors can only be guaranteed for a limited number of switching processes.

There are also dangers for humans from electric arcs:

- **Burns:** If the person's body is near the electric arc or the person comes into direct contact with the electric arc, this causes severe burns as a result of the high temperatures. Do not touch the electric arc! Only handle the conductor using protective gloves!
- **UV radiation:** Through the meeting of the charge carriers not only heat arises, but also light with ultraviolet (UV) elements is radiated. The UV light can cause damage to the eye, and more specifically the retina. One talks about electro-ophthalmia in this case. Never look into an electric arc without a protective mask!
- **Particles flying around:** In the case of an electric arc ions and electrons are constantly being ripped from the conductor material under high temperatures. Smaller parts can also come out with "broken" bits which then fly around uncontrollably. These are often blistering hot! Never approach an electric arc without protective clothing (including protective gloves and eye protection)!

If you are confronted with an electric arc in the workshop operation, please follow the rules below:

⚠

Attempt to shut down the voltage source with the intended devices (e.g. high-voltage service disconnect)!

Keep away from the electric arc and do not look into it!

If you have to approach the electric arc, wear the corresponding protective equipment (protective clothing, eye protection, protective gloves), as prescribed for welding work.

Wear protective clothing	Wear eye protection	Wear protective gloves
		

Avoiding electric arcs

Due to the dangers posed by electric arcs they must be avoided. A variety of technical measures have been implemented so that no electric arcs occur at the components of high-voltage vehicles. The dangers mentioned in the previous chapter therefore rarely occur for service employees. By observing the following rules, the occurrence of electric arcs in high-voltage vehicles can be reduced further:

⚠

Never disconnect high-voltage cables as long as the high-voltage system is still in operation and the lines are carrying a current. Before the high-voltage cables are disconnected, disconnect the high-voltage system from the supply, secure against switching back on again and verify safe isolation from the supply.

1.3. Safety rules for averting danger

1.3.1. Basic information

Each service employee bears responsibility for working safety:

- He must observe instructions and rules for safety and health protection.
- He must use the available protective equipment.
- He must use the equipment (tools, vehicles) according to regulations.
- If defects are identified with the equipment, he must ensure proper elimination. If he is not capable, he must inform his superior so that he can ensure its proper elimination.

There are safety rules for working on components which operate at dangerous voltages. These are binding in Germany under the statutory German Social Accident Insurance regulations (e.g. DGUV regulation 3, §6), as well as internationally through the relevant standards (e.g. DIN ECE R 100). These regulations have been recently adapted in Germany to AC voltages (AC) of **50 V** or higher and for DC voltages of **75 V** or higher.

However in the US market there are no officially mandated regulations regarding the determination of lethal voltages. The industry determines any voltages higher than AC voltages (AC) of **30 V** and for DC voltages of **60 V** to be considered lethal to humans and contact with these voltage should be avoided at all costs.

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High voltage is defined as voltage in range 30–1000 V_{ac} or 60–1500 V_{dc}
http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2013/R100r2e.pdf

Dangerous voltages according to the US market are:

- AC voltages (AC) of **30 V** or higher
- DC voltages of **60 V** or higher

The definition of a "dangerous voltage" is based on the effects which occur if a person comes into contact with an active, live part. The voltage is "dangerous" if the current flowing through the human body can damage health. In high-voltage vehicles, the components which operate at dangerous voltages are summarized under the term "high-voltage components". They are either identified by the following warning sticker or have the warning color orange (high-voltage cables).

High-voltage component warning sticker

The number one safety rule is:

Do not work on actively live parts!

Therefore before starting work ensure the system is de-energized and this state is guaranteed for the duration of the work. Specific, detailed safety rules can be deduced from this number one safety rule. Each service employee must apply these rules before starting work on high-voltage components. Only by complying with these rules is the protection of health and one's life guaranteed.

These safety rules (i.a.w. DIN VDE 0105) are:

1. Disconnect the system from the power supply.
2. Provide a safeguard to prevent unintentional restarting.
3. Establish that the system is isolated from the power supply.
4. Earth and short circuit.
5. Cover neighboring live parts.

Only rules 1 to 3 apply for current vehicles with high-voltage systems. These will be described in detail in the following chapters.

Rule 4 cannot be applied correspondingly as the high-voltage vehicle electrical system has the IT network form. No conductor is connected with "earth" or "ground" there. Earthing thus results in no additional protection. A short-circuit is also not reasonable as other, additional dangers may arise.

These dangers more than offset the benefit. Example: If the voltage at the short-circuit high-voltage battery is switched back on again, than a very high short-circuit current would flow. This can cause the high-voltage battery to go on fire!

Rule 5 is not applicable for current vehicles because there is only one high-voltage vehicle electrical system. This rule is intended for technical installations with several circuits operating with dangerous voltages which are located next to each other. In such installations, only the circuit on which work is performed is usually disconnected from the supply. Covering ensures that no danger arises from the neighboring circuits which remain in operation during the work (e.g. short circuit to the isolated circuit).

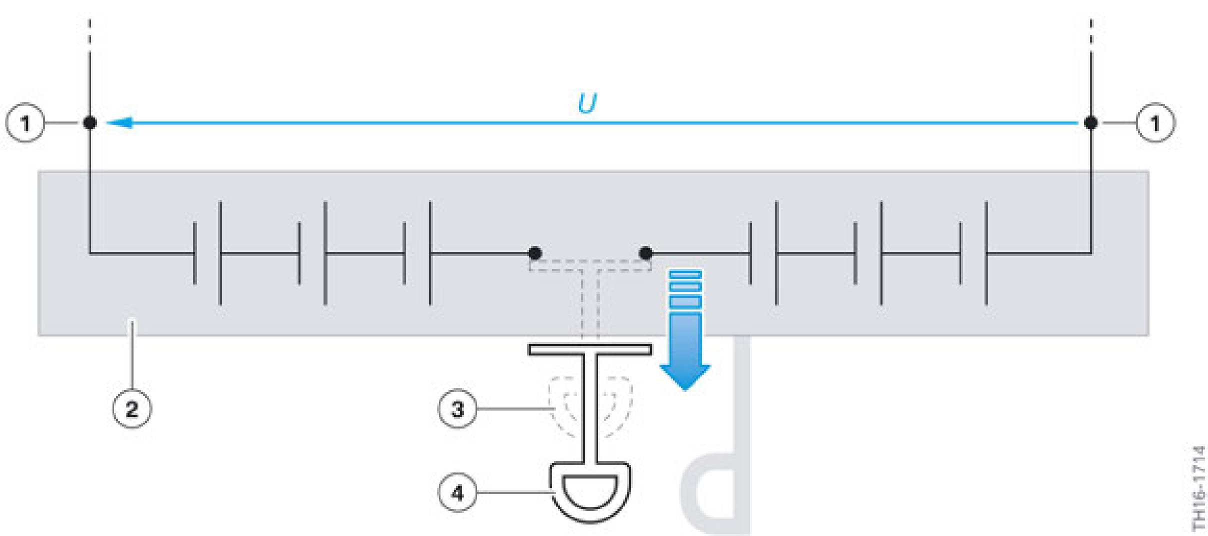
1.3.2. Disconnect the system from the power supply

When carrying out work on high-voltage components, service employees can touch components such as the connections of high-voltage cables. During driving operation, these active components carry a dangerous voltage. So that no danger of health damage arises for the service employee while working, a dangerous voltage must no longer be present at any high-voltage components. For this purpose, the electrical energy source, i.e. the high-voltage battery, is disconnected.

There are two methods to do this.

"Physical" separation

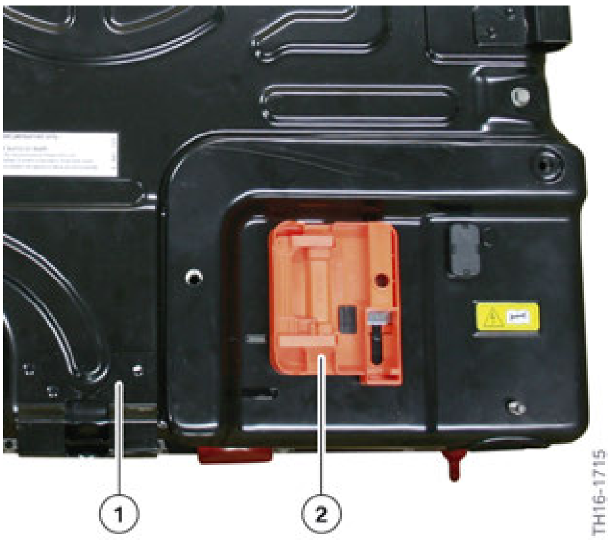
The connection of the series-connected battery cells is disconnected by pulling a plug. There is then no longer a voltage present at the externally accessible terminals of the high-voltage battery. The connector at which the connection can be separated is referred to as the “high-voltage service disconnect” or “Service Disconnect”.



Safety rule 1: Disconnect the system from the power supply

Index	Explanation
1	External connections of the high-voltage battery unit
2	High-voltage battery unit housing
3	High-voltage service disconnect in connected state
4	High-voltage service disconnect in disconnected state

The Service Disconnect has different visual and technical designs in current high-voltage vehicles. Only the design on a BMW ActiveHybrid X6 (E72) is shown here by way of example. This is currently the only series hybrid vehicle of the BMW Group where the Service Disconnect is designed as described above.



Service Disconnect in the BMW ActiveHybrid X6

Index	Explanation
1	High-voltage battery
2	High-voltage safety connector (Service Disconnect)

"Logical" separation

Alternatively to disconnecting the series-connected battery cells, there is also another operating principle of Service Disconnect that is currently used. Here, the Service Disconnect acts as a control input for a control unit. The latter immediately interrupts the supply to the switch contactors as soon as it recognizes disconnection of the Service Disconnect. The contacts of the switch contactors then open automatically.

The effect is the same as for disconnection of the battery cells connected in series. There is no longer a dangerous voltage present at the external connections of the high-voltage battery unit when the Service Disconnect is disconnected.

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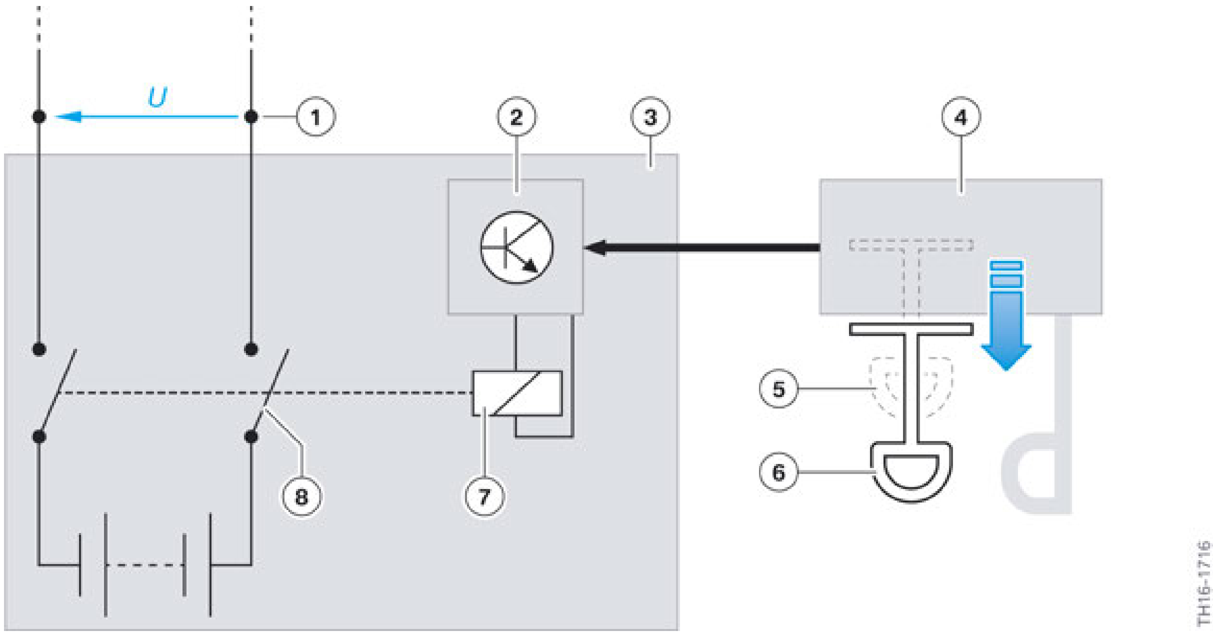

Safety rule 1: Disconnect from supply ("Logical" separation)

Index	Explanation
1	High-voltage connections of the high-voltage battery unit
2	Control unit that evaluates the state of the Service Disconnect and operates the switch contactor correspondingly
3	Housing of high-voltage battery unit
4	Separate housing for Service Disconnect
5	High-voltage service disconnect in connected state
6	High-voltage service disconnect in disconnected state
7	Switch contactor solenoid
8	Switch contactors

The Service Connect has the design as described above in BMW vehicles of hybrid generation 3.0.

Service Disconnect in the BMW 740e iPerformance

When the Service Disconnect is disconnected, several operations take place in parallel and automatically in the high-voltage system. This ensures that there is no dangerous voltage either at the terminals of the high-voltage battery unit, at the electronic components or at the electrical machine(s):

1. Disconnection of the series-connected battery cells or/and opening of the switch contactors in the high-voltage battery.
2. Discharge of the capacitors in the other high-voltage components.
3. Short-circuiting of the windings of the electrical machines.

This eliminates the greatest danger for the service employee. But what if a colleague were to plug in the Service Connect again (either intentionally or unintentionally)? It would then be possible that a dangerous voltage is present again at the components on which work is currently being performed, therefore putting the service employee at risk. For this reason, the high-voltage system must not just be disconnected but also secured against being switched back on again.

1.3.3. Provide a safeguard to prevent unintentional restarting

After the service employee has disconnected the Service Disconnect, he can also secure the high-voltage system there to prevent it from being switched back on. For this purpose, he must fit the standard padlock. By locking the Service Disconnect, he can then prevent this from being inserted again. The service employee most store the key to the padlock in a safe place or carry it on him as long as the work on the high-voltage system is being performed.

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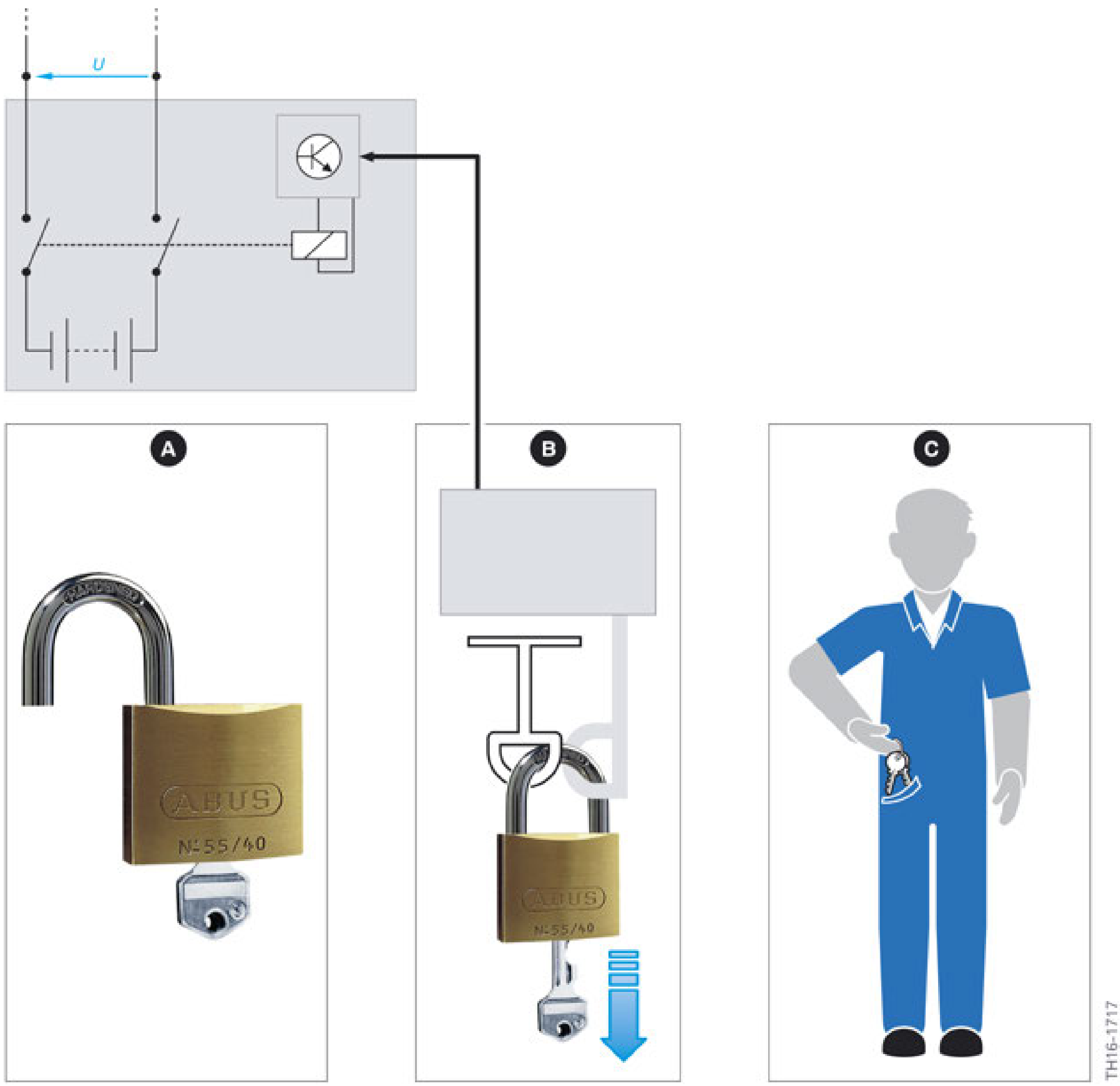


Safety rule 2: Provide a safeguard to prevent unintentional restarting

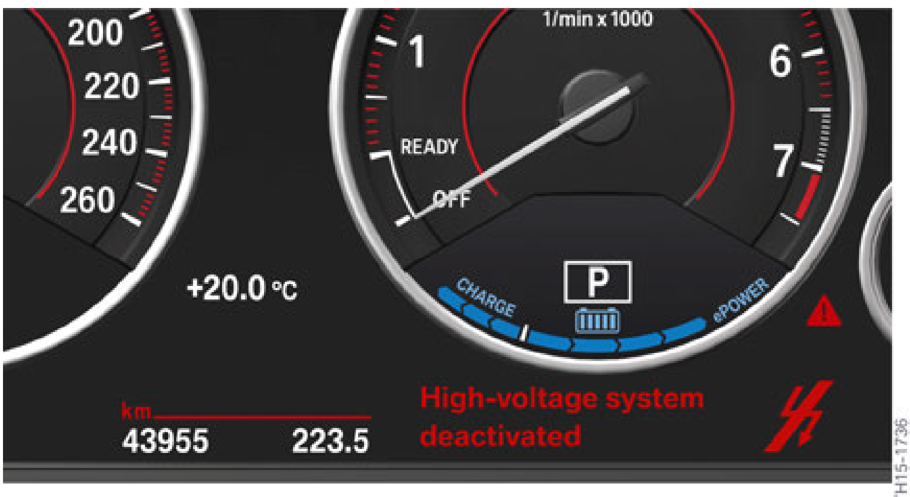
Index	Explanation
A	Use open padlock
B	Lock Service Disconnect in pulled condition using padlock
C	Store key for padlock safely

This measure ensures that no other person can put the high-voltage system back into operation as long as the work is taking place. This excludes any danger to the service employee working on the high-voltage system not just at the start, but also for the entire duration of the work.

1.3.4. Establish that the system is isolated from the power supply

After the service employee has already disconnected the high-voltage system and secured it to prevent it from being switched back on, he must observe and implement a further safety rule. He must verify that the high-voltage system is actually safely isolated from the supply. In BMW vehicles, there is no provision for this to be performed using measuring techniques. The high-voltage system is designed so that it can automatically determine de-energized state.

Several high-voltage components measure the voltage themselves using integrated voltage measurement modules. The measured results are transmitted to the instrument cluster via bus systems. If all measuring results give a voltage value under the dangerous limit, the instrument cluster displays that the high-voltage system was shut down successfully and is actually in a de-energized state.



Check Control symbol: "High-voltage system deactivated"

In this Check Control symbol, the danger symbol for high voltages (lightning) is struck through. It therefore shows in a clear way that there is no longer a dangerous voltage present. The type of display may differ from the symbol shown here depending on the vehicle type. The corresponding display for the respective vehicle type must be determined using the repair instructions or the training media.

The service employee must also observe and carry out this third safety rule before starting work on high-voltage components. In this way, he checks whether the high-voltage system has been properly disconnected. This ensures that there is no danger to the persons working on the vehicle due to the high-voltage system.

1.4. Other dangers by hybrid technology

Chemical energy storage devices (high-voltage batteries) are used for the electric drive in high-voltage vehicles. These contain so-called hazardous substances which require particularly careful handling. The relevant information is binding and documented in safety datasheets. This product information only summarizes the key background information and possible risks and dangers.

1.4.1. Lithium-ion battery

The lithium-ion batteries used in BMW vehicles are not dangerous when used for their intended purpose and if they are not damaged. Intended use is, however, quite limited. In particular, lithium-ion batteries must not be overcharged or subjected to excessively high temperatures.

In the case of overcharging metallic lithium can accumulate at the positive electrode and destroy the negative electrode. In this case high temperatures arise and the lithium-ion battery may catch fire. In BMW high-voltage vehicles, the control unit of the lithium-ion battery ensures that the charging and discharging procedures take place under specified conditions. With help of sensors the cell temperature and cell voltage are monitored. If required, the control unit intervenes in the charging or discharging procedure. This applies both in driving operation and if the high-voltage battery is charged by a charger connected to the 12 V system.

⚠

A lithium-ion battery must not be operated or charged without the respective control unit. Otherwise there is a risk of fire!

A lithium-ion battery cannot be exposed to high temperatures. The service life is already reduced above an operating temperature of approx. 50° C (122° F) . If the cells heat up to 100° C (212° F) or more, this can cause a short circuit of the cells. The high currents that then flow increase the temperature further so that a chain reaction may arise. This destroys the entire lithium-ion battery and may also cause a fire.

It is difficult to extinguish a lithium-ion battery on fire. There is, however, no direct explosion hazard from the battery itself. As a result of the high temperatures arising during the fire, objects in the surrounding area, liquids or gases may ignite however and it can ultimately lead to an explosion.

⚠

The lithium-ion battery on fire can only be extinguished by professional personnel. A burning lithium-ion battery cannot and must not be extinguished with water. The water would react violently with the lithium and release further heat.

Since the operating temperature is strictly limited in upward direction, lithium-ion batteries in BMW high-voltage vehicles are cooled. They can be connected directly to the refrigerant circuit of the air conditioning, for example. When working on lithium-ion batteries, it is therefore necessary to observe the repair instructions and safety data sheets particularly when undoing the connections to the refrigerant circuit.

⚠

The repair instructions for working on the refrigerant circuit – also on lithium-ion batteries – must be followed exactly in order to exclude damage to health.

High-voltage Safe Working Practices

1. Safe Working Practices

⚠

The safety data sheet for handling the refrigerant used (e.g. R134a) must be observed. In particular, the personal protective equipment must be used.

⚠

The safety datasheet, as well as the warning signs and prohibitory signs on the labels on the lithium-ion battery, must be followed in all cases.

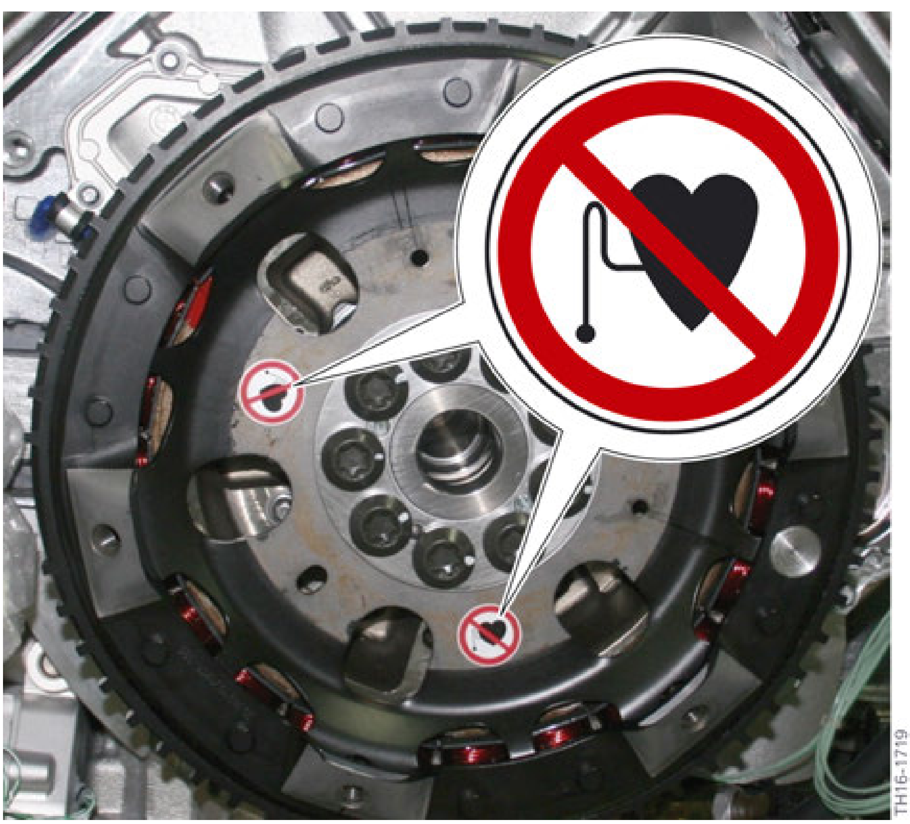
Lithium-ion battery

Index	Explanation
1	High-voltage battery unit warning sticker
2	Prohibition symbol: No flames or smoking
3	Warning symbol: Warning against dangers of batteries
4	Warning symbol: Warning against explosive substances / materials
5	Warning symbol: Warning against caustic substances / materials
6	Type plate with technical data
7	High-voltage component warning sticker

1.4.2. Electrical machines

Due to the high power of the electric drive in BMW high-voltage vehicles, the electrical machines used to operate with strong magnetic fields. These are generated by permanent magnets or electromagnets. Particularly if the magnetic fields are generated by permanent magnets, these fields are always present, even if the high-voltage system is switched off or the electrical machine removed.

These magnetic fields can interfere with operation of electronic medical devices, particularly cardiac pacemakers. The components are marked with a prohibitory sign to point out this danger. The following illustration shows the prohibitory sign on an electrical machine by way of example.



Prohibition symbol: Prohibition for persons with a cardiac pacemaker

⚠

Persons who wear a cardiac pacemaker or other electronic medical devices in order to maintain their health must not work on components that are marked with the following prohibitory sign.

1.5. First-aid measures

1.5.1. Basic information

The technical safety precautions of the high-voltage system in BMW high-voltage vehicles effectively prevent any danger arising for humans. Nevertheless, if an accident with an electrical current should occur, it is important to know how one can properly help the person involved in the accident. This section of the Product Information addresses this topic.

For many people first-aid measures on persons involved in an accident or injured persons are a difficult issue. Often the fear of doing something wrong holds a person back. However, everyone can help. Even if it is "just" calling for emergency medical assistance, you are already doing something right and helping the person who has had an accident or injured. Everyone also has a moral obligation to help an injured person. In some countries it is even a legal obligation.

It is not possible to convey all the relevant topics on first-aid measures in this training media. Only some basic rules are shown and details provided on special measures for electrical accidents.

The local medical service or emergency service (Red Cross) provide training courses with whose help one can obtain not only comprehensive knowledge but also practical skills on the topic of first-aid measures.

As encountering a person involved in an accident is generally unexpected and is also an exceptional situation for the person providing assistance, it is recommended to mentally prepare for such a situation in advance. One should not start straight away or too quickly with performing first aid, but proceed according to the following pattern:

1 Identify

2 Think

3 Act

High-voltage Safe Working Practices

1. Safe Working Practices

Step 1: Identify an electrical accident

The first step - **Identify -** is important particularly for electrical accidents because the remaining procedure is heavily dependent on it. How can one identify that it is an electrical accident? The following features are characteristic of an electrical accident:

- The person involved in the accident is still in the accident circuit. The person cannot move because the muscles are cramping as a result of the electrical current flowing through the body.
- One (or several) person(s) is (are) unconscious on the floor. In the case of high body currents, the heart stops beating, the circulation comes to a standstill - unconsciousness is the result.
- The body of the person involved in the accident has selective burns. There is always a point of entry and a point of exit of the electrical current in to and out of the body.
- Persons involved in an accident may be in shock. Hyperactivity or apathy are possible signs of this.

Step 2: Think

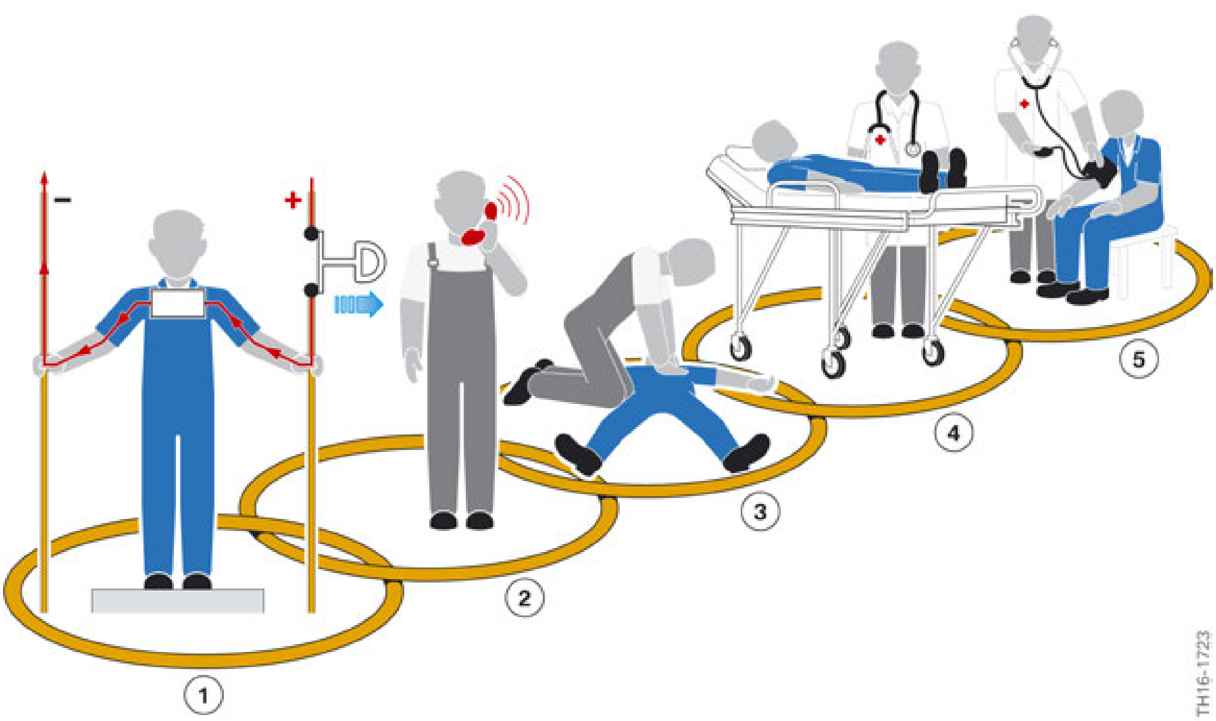
High-voltage Safe Working Practices
1. Safe Working Practices

In the second step one **thinks** about what to do in what sequence. Self-protection is first and foremost particularly in the case of electrical accidents. If the emergency services staff member is in danger or injures himself, he cannot or can no longer help the person involved in the accident.

3rd step: Act

Only when one is clear about the sequence of measures, is it appropriate to **act** swiftly and logically. If other persons are present, one should also convey specific tasks to them. This way the help can be given more effectively and quicker than if only one person had to do it.

The overall objective of all acts for first aid is that the person involved in the accident survives the accident without any damage to his health or as little as possible. It is therefore necessary that the help is provided as quickly as possible also when it is provided by non-professionals. In addition, further steps are necessary and can only be performed by medically trained persons so that a full recovery can be made. All individual steps must be carried out (in the correct sequence). Only then is the so-called rescue chain complete and intact.



Rescue chain

Index	Explanation
1	Immediate measures
2	Transmit emergency call
3	First-aid measures
4	Help by emergency service
5	Medical aftercare

The individual links of the rescue chain are described in the following chapters. Details are provided on the features of accidents with electrical current.

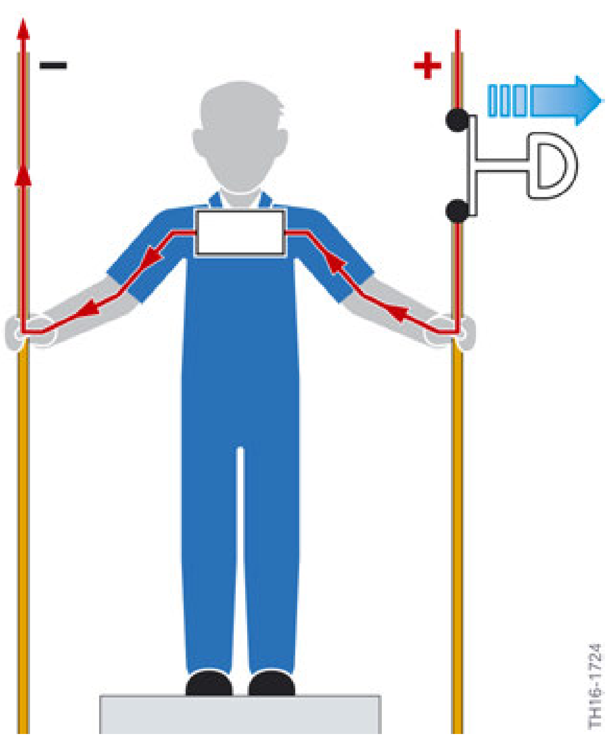
1.5.2. Immediate measures

The term "immediate measures" includes acts which have to be performed first in order to rescue the life of the person involved in the accident. However, it is important that the person providing the assistance assesses the accident situation and identifies that it is an accident with an electrical current for example.

⚠

The first immediate measure for accidents with an electrical current is to interrupt the accident circuit.

It is already known that an electrical current flow flowing through a person's body can cause severe injuries. These become more severe the higher the current level is, but also the longer the current flow lasts. For this reason, the accident circuit must be interrupted as the first measure.



Interrupting the accident circuit

1. Safe Working Practices

The natural reaction of each person providing help is probably to hold the person involved in the accident and pull him away from the live component. But then the person providing the help also puts himself in danger! The current then flows through the bodies of two persons and can also injure the person providing the help. It is therefore particularly important that the person providing the assistance properly assesses the situation and also considers his own protection.

⚠

Self-protection takes top priority during the emergency services. The person providing the aid cannot touch the person involved in the accident directly to interrupt the accident circuit. Instead the voltage source must be shut down with help of the intended equipment.

The following possibilities are available for switching off the voltage source of the accident circuit on high-voltage vehicles:

- Disconnect the Service Disconnect
- Disconnect the 12 V power supply (e.g. by disconnecting the 12 V battery)
- Remove fuse (if present)

If it is not possible for the person providing the aid to shut down the voltage source without harming himself, then the accident circuit must be interrupted another way. The person providing the help requires insulating auxiliary materials or insulating protective gloves. Only with these can the person providing the help try to separate the person involved in the accident and the live part.

In exceptional cases one can also manage with plastic or dry wood parts located nearby and remove the person involved in the accident from the circuit. The risk of the person providing assistance suffering an electric shock themselves is low or excluded only if such auxiliary materials are used.

Insulating protective gloves

1.5.3. Transmit emergency call

Professional medical assistance must be requested for each accident by an electrical current. This is effected by placing an emergency call by telephone or mobile phone. Placing the emergency call is of course also important for other types of accidents, in particular if the person involved in the accident is unconscious or is visibly severely injured.

TH16-1726

Transmit emergency call

Each service employee must know the emergency call numbers valid at his place of work.

The correct emergency call number is **911.**

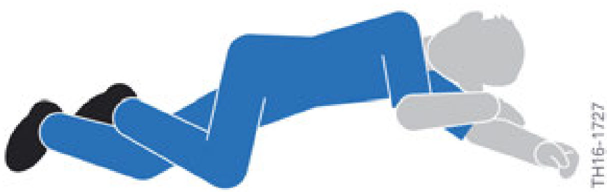
In the case of an emergency call the following information must be provided to the party in the emergency services:

- Where did the accident happen?
- What happened?
- How many persons are injured?
- What type of accident or injury is it?

1.5.4. First-aid measures

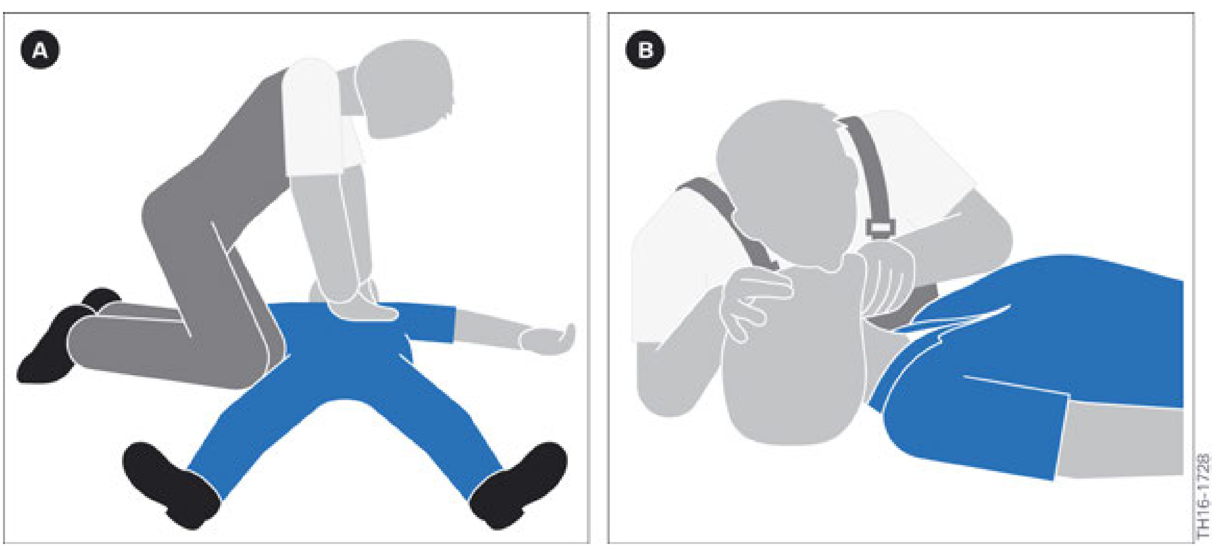
The first-aid measures are necessary if the person involved in the accident is no longer conscious and/or breathing. They are used to maintain vital functions until the emergency service comes on the scene of the accident. Also looking after injuries is part of the first-aid measures.

A person involved in an accident who is unconscious but still breathing must be brought into a stable lateral position.



Stable lateral position

If the person involved in the accident is unconscious and no longer breathing, CPR must be started straight away.



CPR

Index	Explanation
A	Chest Compressions
B	Mouth-to-mouth resuscitation

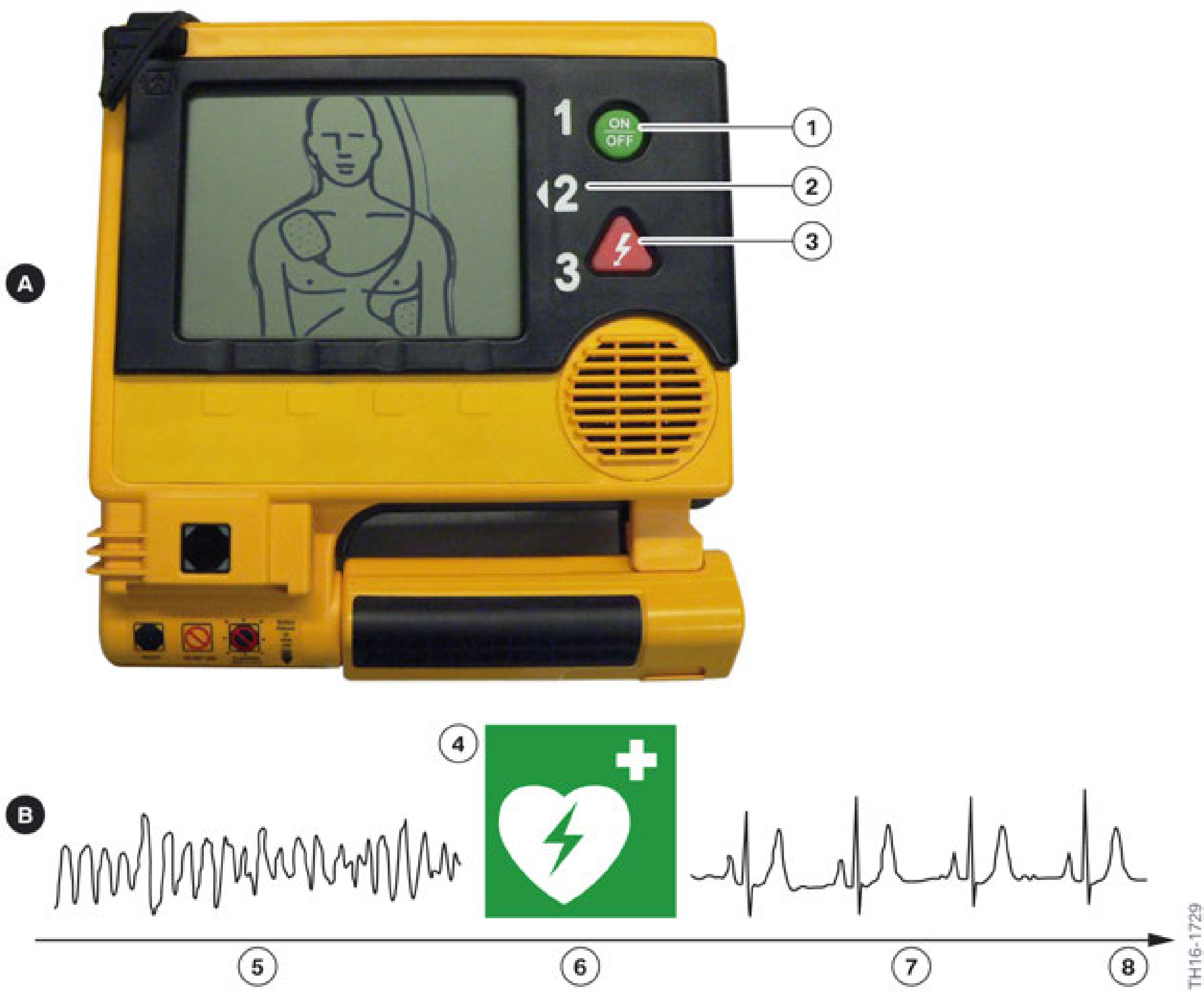
The CPR involves an alternating chest compressions and mouth-to-mouth resuscitation. It must be continued until the person involved in the accident is breathing again or the emergency services arrive.

High-voltage Safe Working Practices

1. Safe Working Practices

In the case of accidents with an electrical current ventricular fibrillations often occur. The heart no longer beats in large, rhythmic movements, but only tiny, highly frequent movements. This state is comparable to trembling during which blood is no longer transported. There is thus an acute danger to life. The person providing the help notices this as respiratory failure and heart failure.

Ventricular fibrillation can be stopped by using a so-called defibrillator and increases the chances of resuscitating the person involved in the accident. Such devices are used by the emergency service. For some time now automatic defibrillators which can be operated by any person have been available. Operating errors are practically ruled out and the device decides automatically whether defibrillation makes sense or not. This type of defibrillator is also known as automated external defibrillator AED.



Automated external defibrillator AED

Index	Explanation
A	Automated external defibrillator (AED)
B	Operating principle
1	Switch on defibrillator
2	Attach electrodes

Index	Explanation
3	Trigger defibrillation
4	Symbol marking storages cabinets or transport bags for defibrillators.
5	Ventricular fibrillations on an electrocardiogram (ECG)
6	Defibrillation
7	Normal heart rhythm on an electrocardiogram (ECG)
8	Time

⚠

If an automated external defibrillator is available, this should be used on persons involved in an accident who are unconscious and no longer breathing.

Burns must be cooled with cold, flowing water until the pain subsides. Then they must be covered with a sterile bandage. If there are burns and also disorders of consciousness and the cardiovascular system, then resuscitation measures take priority.

In-depth knowledge and practical activities for first-aid measures can be acquired in courses which are provided by local medical services or emergency services.

1.5.5. Help by emergency service

The work of the emergency service follows on directly from the first-aid measures. Through continuation of CPR, use of a defibrillator and/or the administration of drugs the health of the person involved in the accident is stabilized or improved. However, the rescue chain is not yet complete.

Help by emergency service

1.5.6. Medical aftercare

⚠

For each accident with an electrical current an examination by a doctor is imperative.

Medical aftercare

The reason for this is that the electrical current not only has short-term harmful effects, but also effects which only appear a few hours, days or even weeks later. For example protein products which have to be excreted by the kidneys build up during the current flow through the body. If the amount of the degradation products is too large, it can also result in renal failure a few days after the accident.

Depending on the severity of the accident, the person involved in the accident must be examined as an outpatient, remain in the hospital under observation or go to a doctor for check-ups. Only with these measures can complications and permanent health damage be avoided.

1.6. Safe work practices for working on high-voltage components

1.6.1. Prerequisites

⚠

Only Service employees who satisfy all the prerequisites are permitted to work on the designated high-voltage components: Valid certificates (for the corresponding component and the corresponding vehicle type), compliance with safety rules, following procedures exactly as described in the repair instructions!

Service employees who have only received basic training on high-voltage vehicles (such as through the Product Information "eDrive in Service") are **not** suitably qualified to perform work on high-voltage components. They are expressly prohibited from working on high-voltage components!

Employees who are to perform work on high-voltage components require the corresponding certification. Firstly, they must be qualified as a "Specialist for work on high-voltage, intrinsically safe motor vehicles" **and** secondly, they must have vehicle-specific certifications for the vehicle type (must have attended ST1507 "F15 PHEV Complete Vehicle” instructor led course and passed the hands-on certification.)

This is the only way to assess the electrical hazards posed by the high-voltage system and define the necessary protective measures for the high-voltage system. Service employees with appropriate qualifications are able to de-energise the motor vehicle, ensure the vehicle remains de-energized throughout the duration of work and perform repairs on the high-voltage system.

The scope of the qualification mainly depends on the educational background and practical experience of the employee. Evidence/certificates of the skills and knowledge acquired through theoretical and practical qualifications is required.

1.6.2. Technical safety precautions

BMW high-voltage vehicles, and particularly the high-voltage components, are designed and constructed to be intrinsically safe. This means that faults which could lead to harming the vehicle user are reliably identified. This leads to an immediate shutdown of the high-voltage system so that dangerous voltage is no longer present at active parts. Shutdown is also automatically initiated if the cover on a high-voltage component is removed, for example.

The high-voltage system is also designed to be fault-tolerant so that the vehicle user does not have to stop because of every fault. This means that there is no direct risk due to the occurrence of a single fault. The self-diagnosis of the high-voltage components detects these faults and they are entered in the fault memory. However, it is possible to continue driving in these cases without any danger.

High-voltage Safe Working Practices
1. Safe Working Practices

The following list provides an overview of the technical safety precautions that are used in the high-voltage system of BMW high-voltage vehicles.

- Identification
- Protection against accidental contact
- High voltage interlock loop
- Discharging of the high-voltage circuit
- Electrical isolation of the high-voltage vehicle electrical system from the 12 V vehicle electrical system
- Short-circuit monitoring
- Shutdown in the event of an accident

How these measures function is described in the following chapters. Some special features are addressed which apply to the safety precautions for the high-voltage cables and the high-voltage battery.

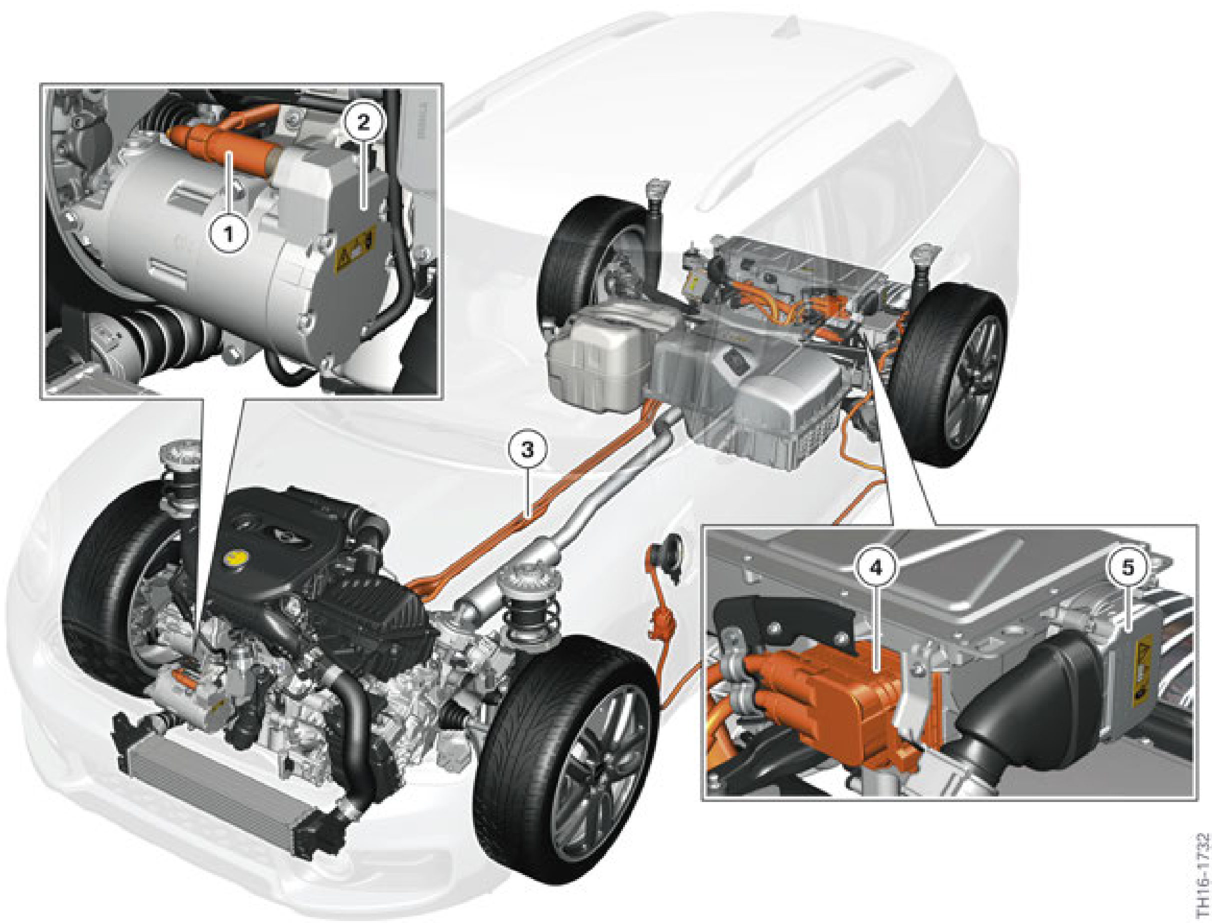
Identification of high-voltage components

Each high-voltage component has on its housing or casing an identifying label that enables Service employees and vehicle users to identify intuitively the possible hazards that can result from the high electric voltages used.

High-voltage component warning sticker

The high-voltage cables are a special case for identification. As they can be several meters long, marking with a warning sticker at one or two places would not make much sense. The Service employee could easily overlook these stickers. Instead all high-voltage cables are marked in the orange warning color. Also some connectors at high-voltage cables, as well as the high-voltage safety connector, can be in orange.

High-voltage Safe Working Practices
1. Safe Working Practices



Identification of high-voltage components

Index	Explanation
1	Orange high-voltage connector (circular)
2	Warning sticker on the high-voltage component
3	Orange high-voltage cable
4	Orange high-voltage connector (flat)
5	Screwed-on high-voltage connector with warning sticker

⚠

Only Service employees who satisfy all the prerequisites are permitted to work on the designated high-voltage components: Valid certification, compliance with the safety rules, procedure exactly as per repair instructions (see also chapter "Prerequisites").

The manufacturers of high-voltage vehicles have agreed on a uniform identification of the high-voltage components with the above-mentioned warning stickers and the warning color orange for high-voltage cables.

High-voltage Safe Working Practices
1. Safe Working Practices

Protection against direct contact

Under protection against accidental contact some basic technical measures at an electrical system are summarized, which when applied can help prevent a person coming into contact with a dangerous voltage component. A distinction is made between two levels: basic protection (protection against direct contact) and fault protection (protection in the case of indirect contact).

The basic protection describes the intensity of the protection under normal operating conditions, i.e. when there is no fault. The basic protection can be specified by the so-called degree of protection in the form of IP codes. The exact make-up of the IP codes is described in the standard IEC 60529. The first two digits (figures) after "IP" indicate protection against external bodies and moisture.

The third character (letter), however, is of interest for the safety of the person: At least the IP code IPxxB applies for a completely assembled high-voltage system in BMW high-voltage vehicles. The letter "B" means that the housing and covers of the high-voltage components are formed and assembled so that it is not possible to touch components carrying a dangerous voltage with fingers. The degree of protection IPxxB is required for the engine compartment, for example, and this requirement is met by the high-voltage system.

The even stricter degree of protection IPxxD must be met at other installation locations in the vehicle. The letter “D” means that it is not possible to touch any components with a dangerous voltage even when using a wire.

Basic protection also includes insulation from active, i.e. live, parts which are located inside and outside the housing.

Protection in case of indirect contact

The second stage, fault protection, includes additional protective measures to basic protection, which prevent danger arising for persons if an electrical fault occurs. This includes:

- Insulation of the high-voltage cables
- System type of the high-voltage vehicle electrical system

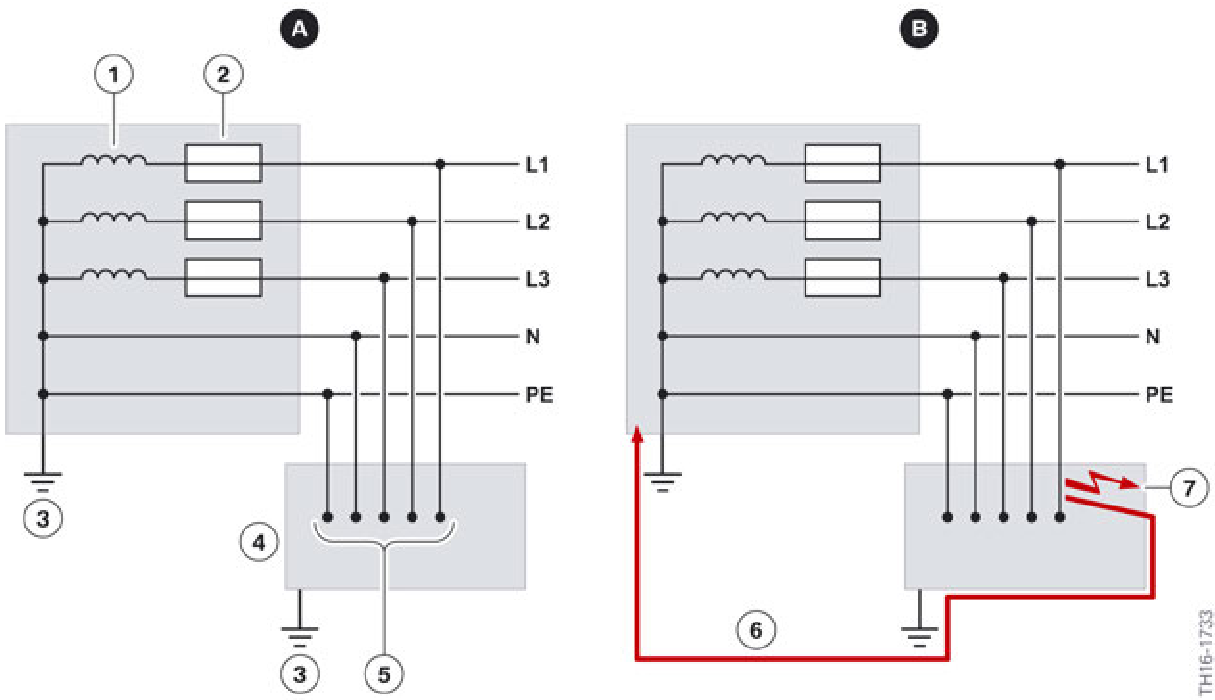
Both protective measures are described in this chapter.

The high-voltage cables have an insulating plastic layer. There is only a shield (braid/foil) over this, which is used for 2 reasons: to reduce electromagnetic interference and primarily for insulation monitoring (also seen later in this chapter). The shield is protected by an orange-colored plastic layer against mechanical damage (e.g. abrasion).

The high-voltage cables must satisfy high requirements in relation to insulation resistance. An insulation resistance of several mega-ohms is required. Compliance with this is checked after manufacture and monitored in operation. With these measures the high-voltage cables satisfy the requirements of protection class II against direct contact.

How can the **system type** of the high-voltage vehicle electrical system contribute to protection of persons in the event of an electrical fault in a high-voltage component? To explain this, a short circuit in a live cable with an electrically conductive housing is considered below. First, a comparison is made with the electrical installation in houses before examining the differences between this and the high-voltage vehicle electrical system in high-voltage vehicles.

The electrical installation in houses consists of a three-phase AC voltage system. There are 3 live conductors (phase conductors) and at least one conductor (neutral conductor and possible a PE conductor) which is earthed. This widely used system type is referred to as “TN”. The abbreviation “TN” stands for “Terre Neutre” (French) and means that the star point of the generator is earthed and an earthed neutral conductor is routed to the domestic connection. Electrically conductive housings are also earthed.



TN system

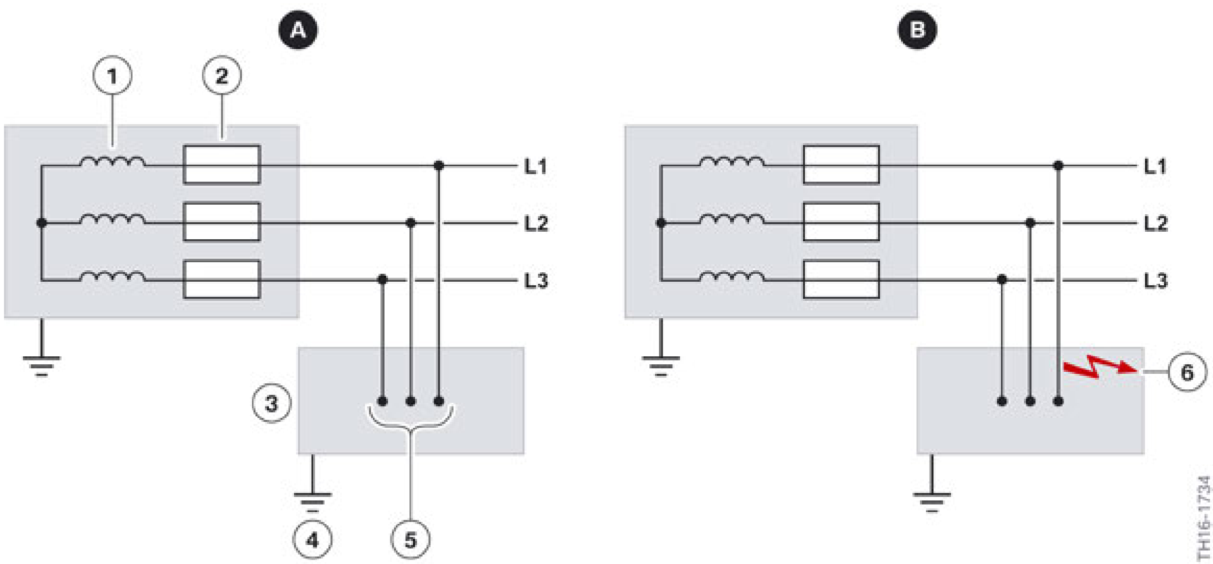
Index	Explanation
A	Design of a TN system
B	Fault situation in a TN system
1	Windings of the feeding transformer or generator
2	Over-current protective devices (fuses)
3	Earth connection
4	Housing of a consumer in the TN system
5	Line connections in the consumer
6	Fault current from the phase conductor L1 via housing and earth connection back to the feeding transformer
7	Short circuit of the phase conductor L1 to the housing of the consumer
L1 ... L3	3 phase conductors
N	Neutral conductor
PE	Protective earth

High-voltage Safe Working Practices
1. Safe Working Practices

The housing protects the user of a device against direct contact with live parts. If there is a fault where there is an electrically conductive connection between a phase conductor and the housing, this means that there is a dangerous voltage present at the housing (short circuit to exposed conductive part). Current flows via the housing to earth and thus back to the generator. In order to protect persons against the dangerous voltage at the housing, an over-current protective device (fuse) is used in these TN systems as a protective measure. This over-current protective device is designed so that it is tripped as a result of the above-described fault and the voltage is switched off. Protection against indirect contact can thus be realized in this way.

If a TN system with over-current protective device were used in high-voltage vehicles, the high-voltage system would have to be switched off already in the event of a single fault (short circuit between phase conductor and housing). This would greatly reduce the availability of the electric drive. This is one of the reasons why a different system type was chosen in high-voltage vehicles, the so-called IT system (abbreviation for the French term “Isolé Terre”) together with insulation monitoring.

In an IT system, no live conductor is connected with earth or with ground in motor vehicles. What happens in an IT system in the case of the fault considered above where a live conductor has a short circuit to the housing?



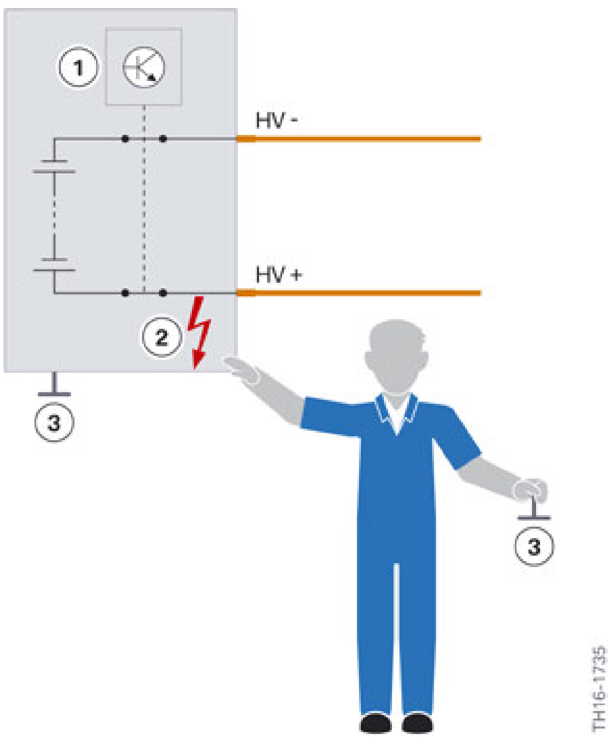
IT network

Index	Explanation
A	Design of an IT system
B	Fault situation in an IT system
1	Windings of the feeding transformer or generator
2	Over-current protective devices (fuses)
3	Housing of a consumer in the IT system
4	Equipotential bonding by earthing
5	Line connections in the consumer
6	Short circuit of the phase conductor L1 to the housing of the consumer
L1 ... L3	3 phase conductors

1. Safe Working Practices

Since the voltage source is not connected with earth (in motor vehicles: with ground), no short-circuit current flows. An over-current protective device will therefore not trip. This means that the high-voltage vehicle electrical system can initially stay in operation with this type of fault. This guarantees high availability of the high-voltage system and is therefore an advantage of this system type.

The IT system cannot just be used for a three-phase system, but also for a DC system of the kind also found in high-voltage vehicles. If a person touches the housing, no current will flow through their body because the circuit to the voltage source is not closed. The current is still not closed even if the person touches the vehicle body (ground) with another part of the body.

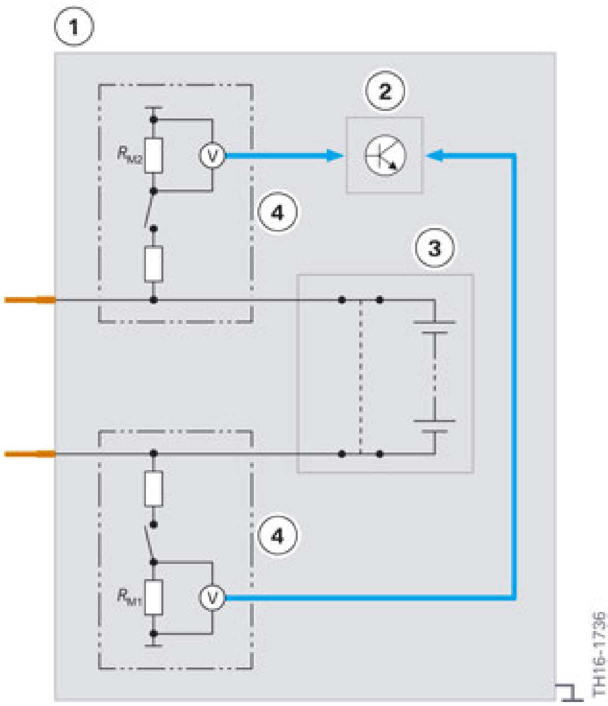


Fault situation in the high-voltage vehicle electrical system

Index	Explanation
1	High-voltage battery unit
2	Short circuit of a high-voltage cable to the housing of the high-voltage battery unit
3	Vehicle body (considered electrically: ground)

A current could flow through a person's body only if they were to additionally touch a second live line of the high-voltage vehicle electrical system. A second advantage of the IT system therefore becomes evident.

However, how can such a fault be detected and then rectified? For this reason, there is so-called **insulation monitoring** in the high-voltage vehicle electrical system. This has the goal of detecting dangerous insulation faults of all active high-voltage components to electrically conductive housings or ground. A dangerous insulation fault is present if a dangerous voltage occurs between housing/ground and a further active high-voltage component. In other words, if the insulation resistance between a high-voltage component and housing/ground has fallen below a threshold value.



Insulation monitoring in the high-voltage vehicle electrical system

Index	Explanation
1	High-voltage battery unit
2	Control unit in the high-voltage battery unit
3	High-voltage battery
4	Circuits for measuring the insulation resistance

The insulation monitoring in the high-voltage vehicle electrical system measures the insulation resistance, e.g. indirectly by means of several voltage measurements. For this purpose, the voltage is measured across measuring resistors between live components (e.g. positive and negative terminals of the high-voltage battery) and ground. Measurements are performed both while the high-voltage system is active and also after the high-voltage system is switched off. The insulation monitoring is normally integrated in one or two high-voltage components, e.g. in the power electronics or/and in the control unit of the high-voltage battery.

How can the insulation monitoring then detect an insulation fault in another high-voltage component, e.g. the electric A/C compressor?

Insulation monitoring from one or two central locations can function only if all electrically conductive housings of the high-voltage components are galvanically (electrically) connected to ground, in other words to the body of the vehicle. This electrical connection has to be present so that a short circuit in a high-voltage cable to the housing of the electric A/C compressor can be detected from the power electronics, for example.

In the absence of this electrical connection between housing and ground the fault would remain undetected and would therefore constitute a potential hazard. The electrical connection of the housings with each other and with ground is called “equipotential bonding”. The electrical connections used for this are called “equipotential bonding conductors”.

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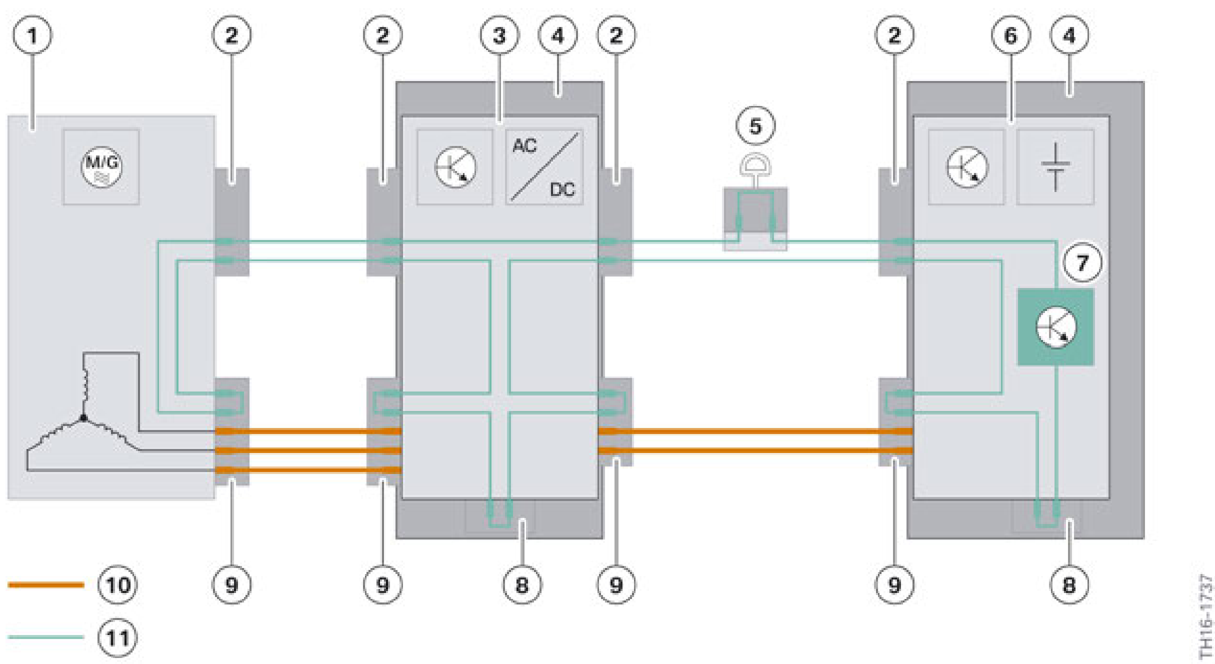
The electrically conductive housings of high-voltage components must have an electrical connection with ground. If in the event of a repair the high-voltage components or also body components are replaced, the following must be observed during assembly: The electrical connection between the housing and the body must be properly re-established. The repair instructions must be followed precisely here also. It is important here in particular to use the specified connecting elements (e.g. self-tapping screws) as well as to comply with specified procedure and tightening torques.

High voltage interlock loop

The active, live parts of the high-voltage components are protected against direct contact by covers or housing. It behaves similarly to the conductors of the high-voltage cables: They are protected against contact by cable insulation or by insulating connector housing. Before working on a high-voltage component, service employees must apply the safety rules to disconnect the high-voltage system. Then all high-voltage components are no longer live and work can proceed in safety. If the service employee forgets to correctly deactivate the system, an extra safety precaution is implemented which leads to automatic shutdown of the high-voltage system.

Covers over a touchable active part and connectors whose contacts can be touched are integrated in the circuit of the so-called high-voltage interlock loop. The principle of the high-voltage interlock loop is shown and explained below.



Principle of the high-voltage interlock loop

High-voltage Safe Working Practices

1. Safe Working Practices

Index	Explanation
1	Electric motor
2	Low-voltage connector for forwarding the test lead of the high-voltage interlock loop
3	Power electronics
4	High-voltage safety cover
5	High-voltage safety connector (Service Disconnect)
6	High-voltage battery unit
7	Electronics for high-voltage interlock loop
8	Bridge of the high-voltage interlock loop at the high-voltage safety cover
9	High-voltage connector with bridge of the high-voltage interlock loop
10	High-voltage cable
11	Test lead of the high-voltage interlock loop

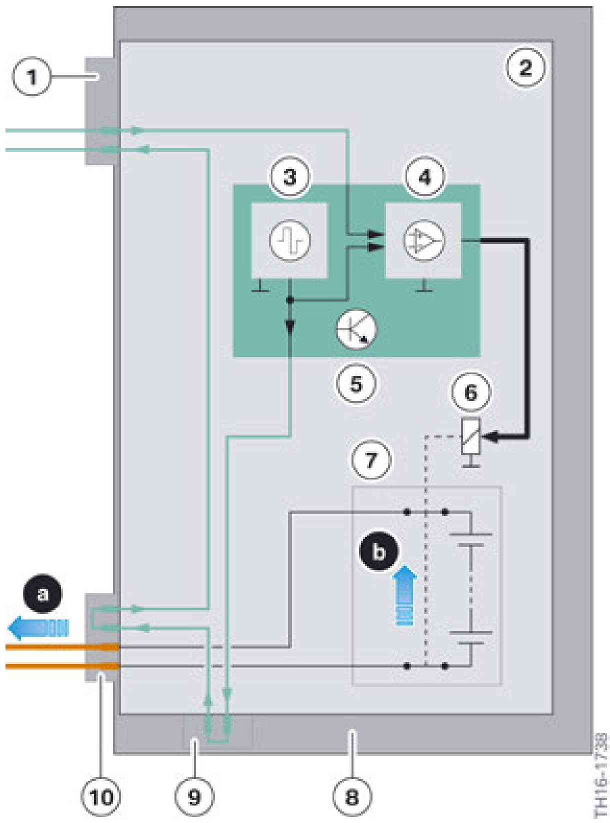
The electronics of the high-voltage interlock loop has two important tasks. The first task is creating the interlock signal. This is AC voltage (or alternating current), which is mostly rectangular and whose values are small and therefore not harmful. The interlock signal is fed in a circuit which runs over the covers of the high-voltage components and/or the connector of the high-voltage cables.

There is a bridge in each of the covers and connectors. If the cover is attached the bridge closes in the circuit of the high-voltage interlock loop. If the cover is removed and thus the bridge drawn, the circuit is interrupted. Similar behavior can be expected at the high-voltage connectors: If the high-voltage connector is inserted, the bridge is closed in the circuit of the high-voltage interlock loop.
If the connector is removed the bridge interrupts the circuit.

The contacts of the high-voltage cables have a retrograde arrangement. This means that first the circuit of the high-voltage interlock loop is interrupted and then the connection of the high-voltage cables. This increases the contact safety and reduces the danger that an electric arc occurs when removing the connection.

The bridges are connected in series in the complete circuit of the high-voltage interlock loop. It is thereby sufficient to remove a cover or a high-voltage connector to interrupt the interlock signal.

The second tasks involves the electronics evaluating the signal at its second connection. As soon as the received high-voltage interlock signal deviates significantly to the sent signal (signal level, short circuit to ground or positive), the electronics triggers a shutdown of the high-voltage system.



Detailed representation of the high-voltage interlock loop

Index	Explanation
a	Removing the high-voltage connector and opening the bridge of the high-voltage interlock loop
b	Opening the contacts of the switch contactor
1	Low-voltage connector for forwarding the test lead of the high-voltage interlock loop
2	High-voltage battery unit
3	Generator for interlock signal
4	Evaluation circuit for interlock signal
5	Electronics of the high-voltage interlock loop
6	Electromechanical switch contactor
7	High-voltage battery
8	High-voltage safety cover
9	Bridge of the high-voltage interlock loop at the high-voltage safety cover
10	High-voltage connector with bridge of the high-voltage interlock loop

The electronics can be part of a control unit of a high-voltage component (e.g. the high-voltage battery). The generator and evaluation circuit for the interlock signal also may be distributed between 2 high-voltage components (e.g. high-voltage battery unit and power electronics).

High-voltage Safe Working Practices

1. Safe Working Practices

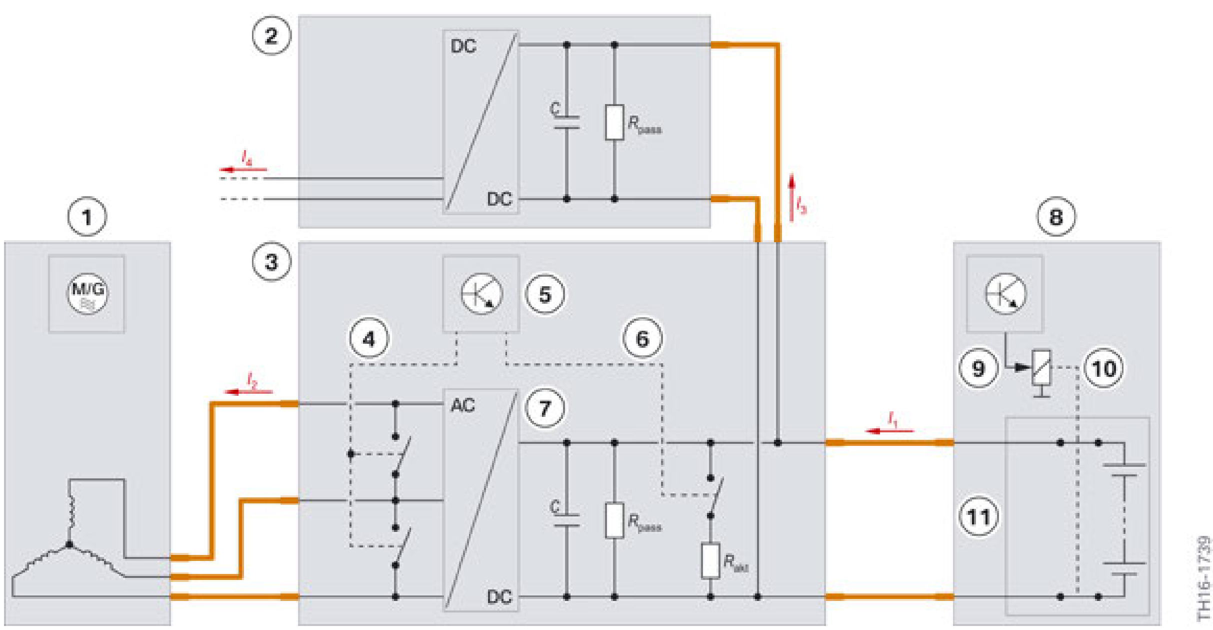
Shutdown of the high-voltage system takes place in several steps as part of an automatically controlled process:

- Cancellation of electrical machine activation.
- Short-circuiting the windings of the electrical machines.
- Opening of the switch contactors in the high-voltage battery.
- Discharging of the high-voltage circuit.

With these measures all possible voltage sources in the high-voltage system are shut down. It is thus guaranteed that at the latest 5 seconds after interruption of the high-voltage interlock loop there is no longer a dangerous voltage present in the entire high-voltage system.

Discharging of the high-voltage circuit

In addition to the high-voltage battery, there are 2 other voltage sources in the high-voltage system: the capacitors in the power electronics (and other high-voltage components) as well as the electrical machine(s). Even if the switch contactors of the high-voltage battery have been opened during shutdown, the capacitors or electrical machine(s) can maintain the voltage in the high-voltage vehicle electrical system at a value which may be dangerous if contact is made by a person. The high-voltage circuit is therefore discharged at each shutdown of the high-voltage system. The following graphics show how discharging takes place using a simplified wiring diagram of high-voltage components. The actual realization of the discharging circuits in high-voltage vehicles may deviate from this simplified diagram.



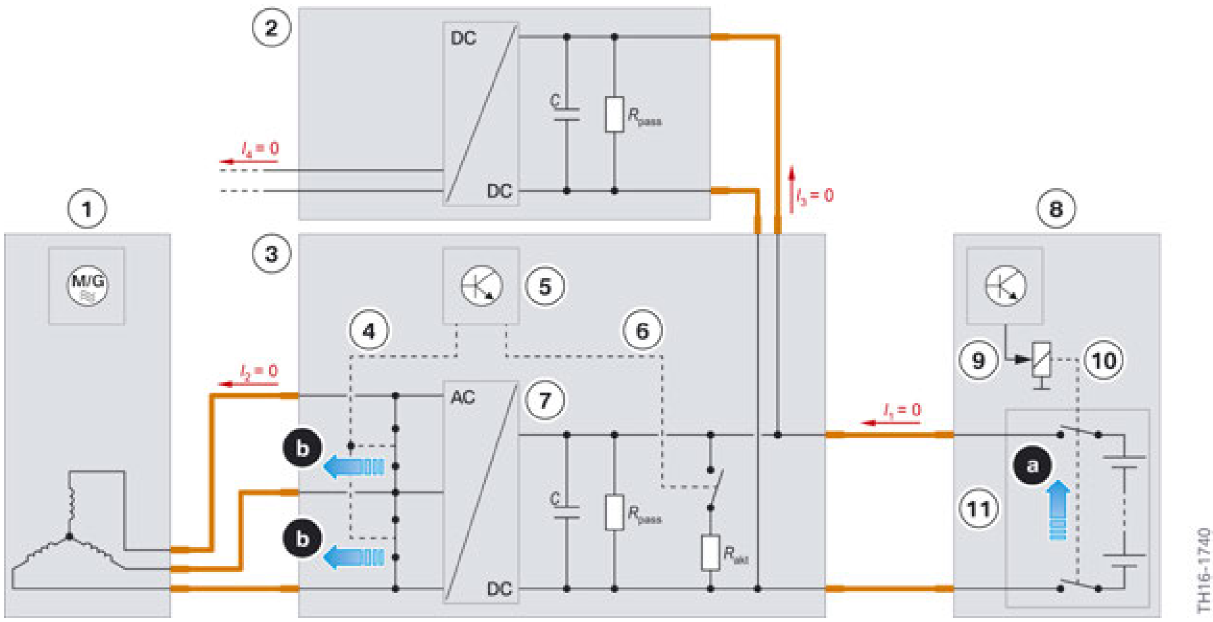
Simplified wiring diagram of the high-voltage system: Active state

Index	Explanation
1	Electric motor
2	DC/DC converter
3	Power electronics
4	Control for short-circuiting the windings of the electrical machine
5	Control unit of power electronics
6	Control for actively discharging the capacitors
7	Power converter in the power electronics, operated here as inverter
8	High-voltage battery unit
9	Control unit in the high-voltage battery unit
10	Electromechanical switch contactor in the high-voltage battery unit
11	High-voltage battery
C	Link capacitors in DC/DC converter and power electronics
$I_1 \dots I_4$	Consumer currents
R_{pass}	Passive discharge resistor
R_{akt}	Active discharge resistor

As long as the switch contactors of the high-voltage battery are closed, the voltage of the high-voltage battery is applied at the high-voltage cables. The capacitor on the direct voltage side of the power electronics has the same voltage and is charged. The power electronics supplies the high-voltage components with electrical energy, a current flows via the high-voltage cables.

Before the switch contactors of the high-voltage battery are opened, the power electronics controls all high-voltage consumers so that they no longer consume any current. In circuit terms, this is equivalent to a condition where there is no longer any consumer connected to high-voltage vehicle electrical system.

The electrical machines could generate a dangerous voltage in the high-voltage vehicle electrical system even if the switch contactors of the high-voltage battery are already open. If the electrical machines were still to turn, a voltage would be induced in their windings. This would be present at the high-voltage cables and can also assume dangerous values for humans, depending on the speed. For this reason, the windings of the electrical machines are short-circuited after the switch contactors of the high-voltage battery are opened.



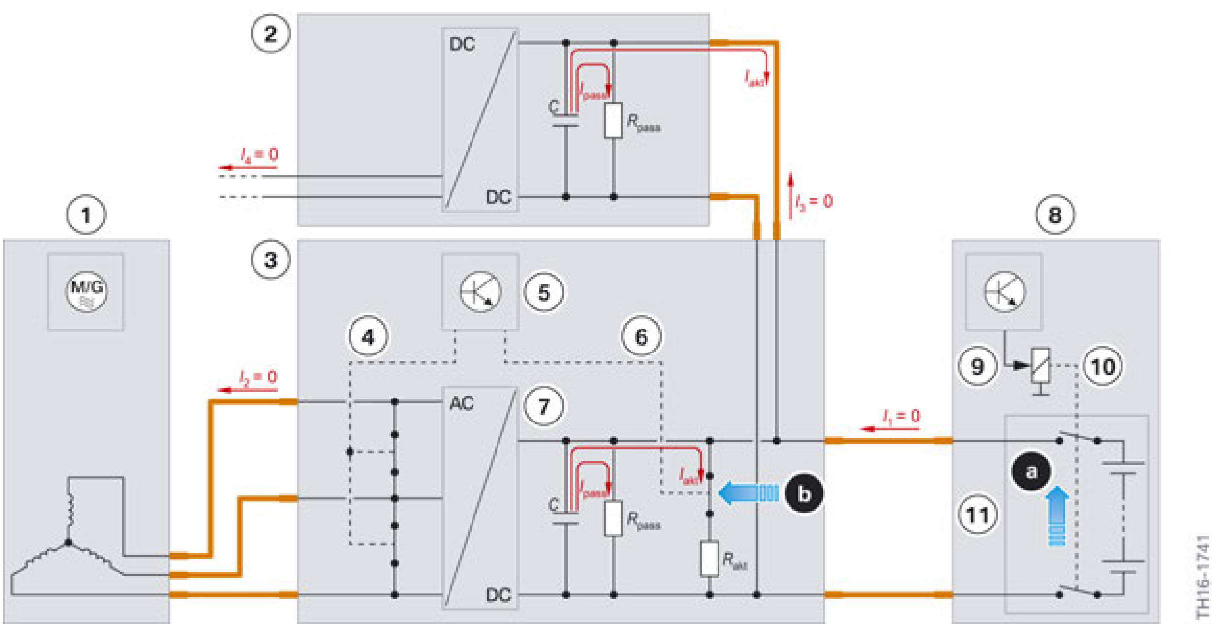
Simplified wiring diagram of the high-voltage system: Short-circuit of the coils of the electrical machine

Index	Explanation
a	Opening the contacts of the switch contactor in the high-voltage battery unit
b	Closing the contacts for short-circuiting the windings of the electrical machine
1	Electric motor
2	DC/DC converter
3	Power electronics
4	Control for short-circuiting the windings of the electrical machine
5	Control unit of power electronics
6	Control for actively discharging the capacitors
7	Power converter in the power electronics, operated here as inverter
8	High-voltage battery unit
9	Control unit in the high-voltage battery unit
10	Electromechanical switch contactor in the high-voltage battery unit
11	High-voltage battery
C	Link capacitors in DC/DC converter and power electronics
I_1 ... I_4	Consumer currents
R_{pass}	Passive discharge resistor
R_{akt}	Active discharge resistor

This operation is controlled by the power electronics in current BMW high-voltage vehicles. Short-circuiting of the electrical machine(s) is particularly important as they can still turn as long as the vehicle is rolling. A dangerous induction voltage can occur in their windings as a result.

With the other electrical machines installed (e.g. in the electric A/C compressor), their design and behavior on switching off determine whether their windings have to be short-circuited. If an electrical machine continues to turn after switching off and induces a dangerous voltage at the windings as a result, its windings will also be switched off. This may vary from vehicle type to vehicle type.

In the wiring diagram one can see that capacitors are used in the power electronics which are connected parallel to the high-voltage cables for example. If the switch contactors of the high-voltage battery are opened, the same voltage as before is still present at the high-voltage cables.
The capacitors store the electrical energy and keep the voltage at this value. Without additional measures the capacitor cannot charge itself because all high-voltage consumers are shut down beforehand. There is a discharge circuit for the capacitors so that the voltage at the high-voltage cables can be reduced. It comprises a so-called passive discharge resistor and an active discharge resistor.



Simplified wiring diagram of the high-voltage system: Discharging of the capacitors

Index	Explanation
a	Opening the contacts of the switch contactor in the high-voltage battery unit
b	Closing the contact for active discharging of the capacitors
1	Electric motor
2	DC/DC converter
3	Power electronics
4	Control for short-circuiting the windings of the electrical machine
5	Control unit of power electronics
6	Control for actively discharging the capacitors
7	Power converter in the power electronics, operated here as inverter
8	High-voltage battery unit
9	Control unit in the high-voltage battery unit

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Index	Explanation
10	Electromechanical switch contactor in the high-voltage battery unit
11	High-voltage battery
C	Link capacitors in DC/DC converter and power electronics
$I_1 \dots I_4$	Consumer currents
I_{pass}	Current through passive discharge resistor
I_{act}	Current through active discharge resistor
R_{pass}	Passive discharge resistor
R_{akt}	Active discharge resistor

The passive discharge resistor R_{pass} is switched on permanently parallel to the capacitor. After the switch contactors in the high-voltage battery are opened, the discharge current flows immediately from the capacitor via the passive discharge resistor. The voltage of the capacitor and thus the voltage at the high-voltage cables drops exponentially and reaches the value 0 V after $t = 5 \times \tau = 5 \times R_{pass} \times C$. A current also flows via the passive discharge resistor when the high-voltage system is active. To keep the arising power loss at an acceptably low level, the passive discharge resistor is designed as relatively high-resistance. The order of magnitude is several 10 kΩ. However, the capacitance values of the capacitors used reach values of several 100 mF. It may therefore take a few minutes until the voltage drops to 0 V with passive discharging. However, the system is designed so that the capacitors are discharged to safe voltage levels via the passive discharge resistor at the latest after 5 minutes.

The passive discharging is, however, only an additional safety precaution if the activation of the active discharging resistor is not functioning. The power electronics controls closing at the active discharge resistor when the high-voltage system is being shut down after the switch contactors of the high-voltage battery have been opened. The active discharge resistor R_{akt} has a value of just a few 10 Ω and permits much faster discharge. This design ensures that the high-voltage circuit is discharged by active discharging after 5 seconds at the latest.

In current high-voltage vehicles, there is usually exactly one active discharge resistor, which is located in the power electronics. When the high-voltage system is shut down, not just the capacitors in the power electronics are discharged via this resistor, but also those in other high-voltage components such as the DC/DC converter or electric A/C compressor. This type of central active discharge is possible because the high-voltage cables and capacitors are connected in parallel in the high-voltage components.

In addition to the active discharge resistor, there are also passive discharge resistors in every high-voltage component with capacitors. These ensure that the capacitors are also discharged even if active discharging fails or if the high-voltage cables between high-voltage components are interrupted before active discharging can be successfully completed.

	Passive discharging	Active discharging
Type of discharge circuit	Continuous	Switched
Number of discharge resistors	One passive discharge resistor in every high-voltage component with capacitors	At least one active discharge resistor in the overall high-voltage system, several possible
Maximum time for discharge	5 minutes	5 s

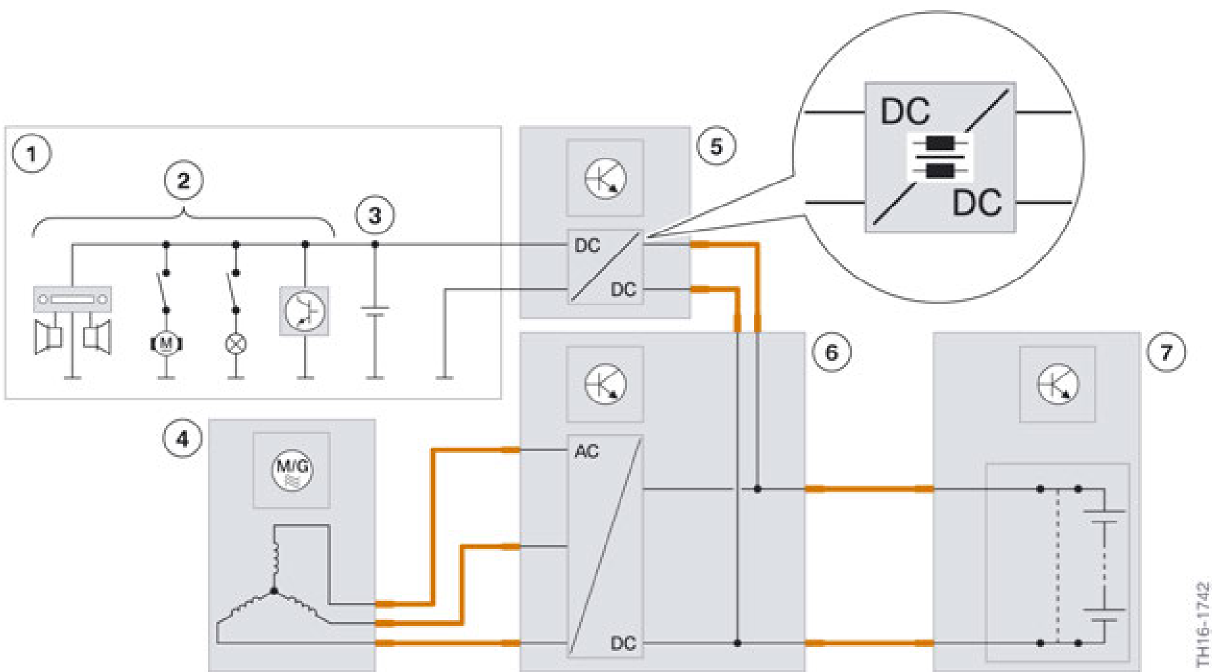
High-voltage Safe Working Practices

1. Safe Working Practices

Electrical isolation of the high-voltage vehicle electrical system from the 12 V vehicle electrical system

In high-voltage vehicles, the high-voltage vehicle electrical system and the 12 V vehicle electrical system have an energy connection via a DC/DC converter. This means that it is possible for the 12 V battery to be charged with energy from the high-voltage vehicle electrical system, for example. A 12 V alternator is then no longer required. With this desired energy connection between the two vehicle electrical systems, it must be ensured that no dangerous voltage from the high-voltage vehicle electrical system is transferred into the 12 V vehicle electrical system. Otherwise the same electrical safety rules would also apply in the 12 V vehicle electrical system as in the high-voltage vehicle electrical system.

The 12 V vehicle electrical system and the high-voltage vehicle electrical system are electrically isolated from each other for this reason, i.e. there is no conductive connection between the two vehicle electrical system. This is achieved by suitable insulation on the components and lines. A circuit must be used in the DC/DC converter which guarantees electrical isolation in spite of the energy connection. A transformer circuit can be used for this, for example. Since no energy can be transmitted between DC voltage systems using a transformer, the DC voltages must be converted into AC voltages and vice versa.



Simplified wiring diagram: High-voltage vehicle electrical system and 12 V vehicle electrical system

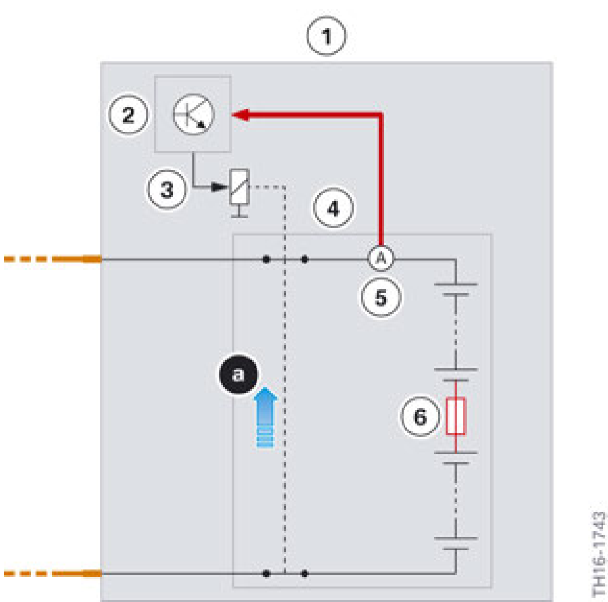
Index	Explanation
1	12 V vehicle electrical system
2	12 V consumer
3	12 V battery
4	Electric motor
5	DC/DC converter
6	Power electronics
7	High-voltage battery unit

Short-circuit monitoring

Short circuits in the high-voltage vehicle electrical system, e.g. between the two high-voltage battery cables, would lead to very high short-circuit currents. The reasons for this are as follows:

- High voltage
- Low internal resistance of the high-voltage battery
- Low resistance of the high-voltage cables

The consequences of such high short-circuit currents would be serious. They range from generation of an arc through destruction of the high-voltage cables or high-voltage battery up to a fire. In order to avoid this, technical measures for detection of a short circuit are implemented in the high-voltage vehicle electrical system of high-voltage vehicles. These are normally integrated in the high-voltage battery unit.



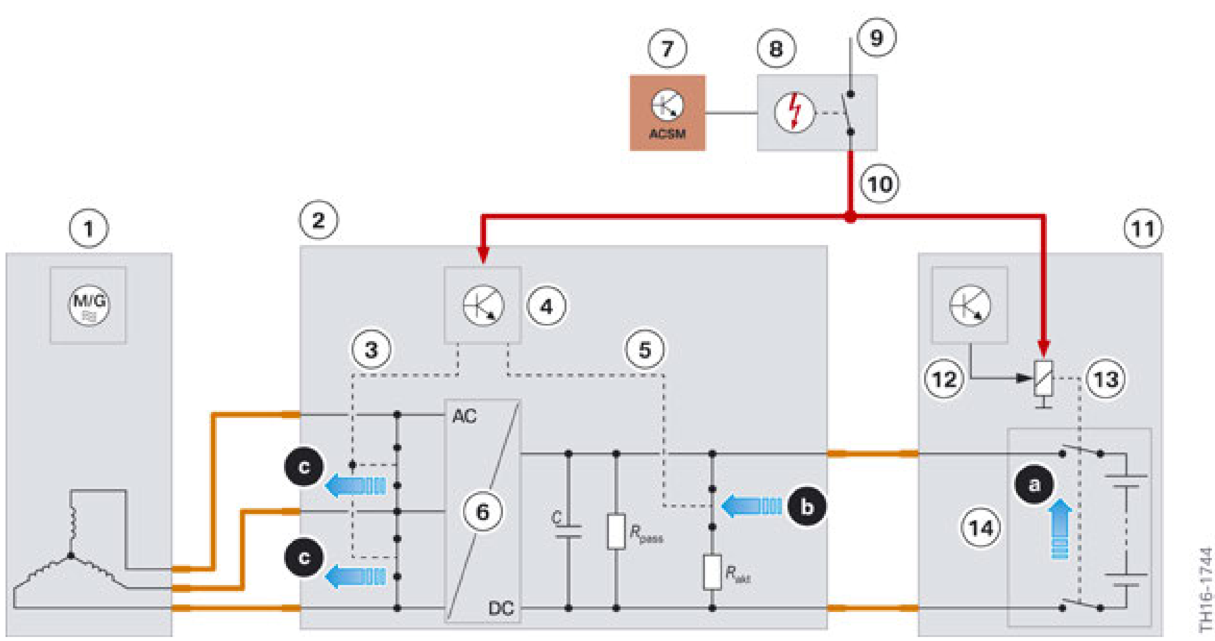
Simplified wiring diagram of short-circuit monitoring

Index	Explanation
a	Opening of the switch contactor contacts when the short-circuit monitoring is tripped
1	High-voltage battery unit
2	Control unit in the high-voltage battery unit
3	Electromechanical switch contactor
4	High-voltage battery
5	Current sensor
6	Safety fuse

High-current safety fuses and electronic excess-current circuit breakers are used. In order to shorten the response time in the event of a short circuit, the current is electronically monitored by means of current sensors in the battery cables. If the control unit of the high-voltage battery unit detects an inadmissibly high current, contact opening of the switch contactor in high-voltage battery is triggered. The switching contacts are designed so that they open reliably even at the high current levels that occur in the event of a short circuit. However, this significantly reduces their service life. The electronic short-circuit monitoring reduces the response time compared with sole use of conventional safety fuses particularly for high current levels.

Shutdown in the event of an accident

In the event of an accident, sparks or arcs can be produced as a result of the high-voltage cables being torn off if the vehicle underbody comes into contact with sharp objects (e.g. crash barriers). In order to minimize this risk, the high-voltage system is shut down in the event of an accident. In current BMW high-voltage vehicles, accident detection and coordination of the safety systems are performed by the Advanced Crash Safety Module (ACSM).



Shutdown of the high-voltage system if an accident is detected

Index	Explanation
a	Opening the switch contactor contacts in the high-voltage battery unit
b	Closing the contact for active discharging of the capacitors
c	Closing the contacts for short-circuiting the windings of the electrical machine
1	Electric motor
2	Power electronics
3	Control for short-circuiting the windings of the electrical machine
4	Control unit of power electronics
5	Control for actively discharging the capacitors
6	Power converter in the power electronics, operated here as inverter
7	Advanced Crash Safety Module (ACSM)
8	Safety battery terminal (extended by additional contact)
9	Terminal 30
10	12 V line interrupted by the safety battery terminal
11	High-voltage battery unit
12	Control unit in the high-voltage battery unit
13	Electromechanical switch contactor in the high-voltage battery unit
14	High-voltage battery
C	Link capacitors in the power electronics
R_{pass}	Passive discharge resistor
R_{akt}	Active discharge resistor

If the Advanced Crash Safety Module detects an accident with corresponding severity, the positive cable of the 12 V battery to the positive battery connection point is pyrotechnically disconnected. The actuator used for this – the safety battery terminal – was extended for BMW high-voltage vehicles. An additional 12 V line is interrupted by the safety battery terminal together with the positive battery cable. This line is used in two ways to shut down the high-voltage system:

1 Opening the switch contactor contacts in the high-voltage battery.
2 Active discharge of the high-voltage circuit.

Opening of the switch contactor contacts is performed without any additional activity of the control unit in the high-voltage battery unit. The 12 V line interrupted by the safety battery terminal is used in the high-voltage battery unit as the supply voltage for the solenoid of the electromechanical switch contactor. If the supply voltage drops out, the contacts of the switch contactor open automatically.

The power electronics uses the 12 V line interrupted by the safety battery terminal as a signal input for active discharge of the high-voltage circuit. If this line is interrupted, the power electronics ensures that the following operations are carried out:

- The windings of the electrical machine(s) are short-circuited.
- The capacitors are actively discharged.

1. Safe Working Practices

Triggering of the safety battery terminal is a signal which is used as a basis for shutdown of the high-voltage system in the event of an accident. However, bus telegrams from the Advanced Crash Safety Module are also evaluated: If the Advanced Crash Safety Module signals an accident with corresponding severity in this ways, the high-voltage system is also shut down.

These technical measures ensure that the high-voltage system is switched off reliably and in a very short time in the event of an accident. Dangers due to high voltages during or after an accident can therefore be practically excluded.

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Before starting work on high-voltage vehicles that have been involved in an accident, the instructions and notices in the following documents in the repair instructions must be observed:

- Safety information for handling electric vehicles.
- Assessment of vehicle that has been involved in an accident.
- Visual inspection of high-voltage battery unit after an accident.

1.6.3. Points to note when working on the high-voltage system

Necessary work

This section deals with the following particular points to note when handling the high-voltage system:

- Visual inspection of high-voltage components
- Diagnostic check
- Connection of body components

Before starting work on a high-voltage vehicle, the high-voltage components must be subjected to a detailed visual inspection. This is generally recommended and is essential in the case of vehicles that have been in an accident. Through the visual inspection, the service employee can identify damaged high-voltage components at an early stage, possibly even before a self-diagnosis function in the high-voltage system has detected a fault.

If, for example, the insulation of a high-voltage cable is damaged, but is not touching a body component, the insulation monitoring will not yet react. A conscientious service employee can already detect this fault status through the visual inspection. The housing of the high-voltage battery should also be subjected to a visual inspection on a damaged vehicle. This can prevent any risk to the health due to leaking electrolyte, for example.

At the end of the repair work on the high-voltage system, the high-voltage components must be checked using the diagnosis system. Depending on the vehicle, this may involve simply reading out the fault memory or starting special service functions. This check polls the result of numerous self-diagnosis processes in the high-voltage system. In this way, it can be ensure that the high-voltage system is in a fault-free and safe condition again after repair work has been performed.

The vehicle body acts as a “large equipotential bonding line” between the housings of the high-voltage components. This electrically conductive connection is a crucial prerequisite for correct functioning of the insulation monitoring.

High-voltage Safe Working Practices

1. Safe Working Practices

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After replacement of coated or painted body components, the repair instructions must be followed exactly for high-voltage vehicles in particular.

A high tightening torque prescribed in the repair instructions may be necessary, for example, so that an electrically conductive connection is established to the supporting part in spite of the coating on a newly installed body component. This is of crucial importance for correct functioning of the technical safety precautions of the high-voltage system. In addition to the tightening torque, it is also essential to ensure use of the prescribed connecting elements, e.g. self-tapping screws.

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