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Principles of Hybrid Technology

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Principles of Hybrid Technology

Model: Generic Hybrid Vehicles

OBJECTIVES

After completion of this module you will be able to:

- Understand the philosophy of BMW EfficientDynamics
- Identify the different methods of classifying hybrids
- Identify the components of a hybrid system
- Explain the characteristic batteries used in high-voltage systems
- Understand and explain the engineered safety elements of BMW ActiveHybrid vehicles
- Explain the necessary three safety rules when working on a hybrid vehicle
- Successfully de-energize a high-voltage system

Introduction

BMW EfficientDynamics

BMW EfficientDynamics is the collective term used in communication to refer various technologies and innovations that interwork to produce a combination of reduced pollutant emissions plus high performance power and sheer driving pleasure.

With BMW EfficientDynamics, BMW has assumed a global leadership role in the race to implement measures to reduce fuel consumption and CO2 emissions.

In the period since spring 2007, one-million-plus BMW new-car owners have already benefited from these endeavours. At this time the range consists of 23 models with CO2 emissions figures of 140 g/km or lower: No other premium carmaker anywhere in the world can produce comparable figures.

But BMW EfficientDynamics is more than just high precision injection, engine start/stop function, or brake energy recovery. In the long term, BMW EfficientDynamics also includes zero-emissions motoring with hydrogen fuel, and in the medium term BMW ActiveHybrid – the combination of internal combustion engine and electric motors in the powertrain.

The first production BMW ActiveHybrid models, the hybrid versions of the BMW X6 and the BMW 7-series, will have matured to production status by late 2009. Consequently, BMW – together with Mercedes-Benz – will rank as Europe's first automobile manufacturers to commence hybridizing their model range in one year.

Principles of Hybrid Technology.

Introduction > Why BMW needs hybrid cars?

Sting

Note the reasons:

Principles of Hybrid Technology.

Introduction > BMW EfficientDynamics strategy

Note the elements of BMW EfficientDynamics strategy:

1 ______________________________

2 ______________________________

3 ______________________________

Principles of Hybrid Technology.

Introduction > Definition of hybrid vehicles

Which of the following is a hybrid vehicle?

Definition of Hybrid Vehicles

This 1906 Griffon Sport was a hybrid, a bicycle fitted with an engine

The term hybrid is derived from the Greek and means of two different origins or of mixed origin. As used in the automotive industry, the term refers to vehicles with two means of propulsion (utilising energy from two different sources) and having two different energy supplies.

What makes these vehicles so special is that the elements combined in this way are established technological solutions in their own right, and the combination of the two can be utilised to produce new and beneficial features.

In adopting the hybrid approach, virtually all carmakers have opted for a combination of internal-combustion engine and electric motor or motors drawing energy from a conventional fuel tank on the one hand and a battery bank on the other.

BMW's hybrid strategy calls for hybrid technology only in circumstances in which the ratio of additional cost to savings are justified. The launchpad is provided by the high-end models with big engines like the BMW ActiveHybrid X6 and the BMW ActiveHybrid 7, because this is where the efficiency potential is largest.

Why was the horse drawn carriage/buggy not considered a hybrid?

In your own words, write down the definition of a hybrid.

Classification of Hybrids by Power Rating

What does BMW ActiveHybrid stand for and what distinguishes it from the hybrid offerings of our competitors? In principle, BMW ActiveHybrid refers to all hybrid-technology-related endeavours undertaken by BMW to achieve even higher efficiency – in this respect "Active" underscores the highly dynamic performance-motoring claim that will remain a keynote characteristic of all hybrid BMW models to come.

BMW ActiveHybrid also refers collectively to the three different modes of hybridization, namely micro hybrid, mild hybrid and full hybrid.

Micro Hybrids

Micro-hybrids constitute the first level in the hybrid-car hierarchy. Micro-hybrid cars have a generator power of 2 to 3 kW and use conventional 12-V battery technology. Power and voltage are both comparatively low, imposing a natural limit on energy recovery during braking and in the overrun phase.

In a micro-hybrid car, the recovered electrical energy is fed into the vehicle's on-board 12 V electrical system. In some cases these systems also have a start/stop function with conventional starter or integrated crankshaft starter generator. A drawback of the start/stop functionality is that frequent run-ups mean accelerated wear of the crankshaft, which has frictionless bearings and is designed for constant rotation. Complexity, additional weight and costs for micro-hybrid cars are not beyond reason. All in all, however, the concept cannot justifiably be expected to return more than 10% savings in energy. Strictly speaking micro-hybrid cars are not true hybrids at all, since they have only one means of propulsion.

Mild Hybrid

Mild-hybrid systems typically use voltages higher than 42 V. Today, some of these systems operate at voltages of 160 V or even higher. The power of the electrical machine represented by the electric motor is in the 10 to 15 kW range. Mild-hybrid systems are generally built around electrical machines that transform some of the kinetic energy in retardation/braking into electric energy that can be stored in batteries. Mild-hybrid systems usually implement a start/stop function with the electrical machine being used to restart the combustion engine when the latter is needed again after shutting down. The electrical machine of a mild-hybrid car is also used to some extent as a booster along with the combustion engine for pullaway and acceleration. Some mild-hybrid systems cut off the fuel supply to the combustion engine if the high-voltage accumulator is adequately charged and the car is travelling at a steady speed up to about 50 km/h. Under these circumstances the car is propelled only by the electrical machine so as to economize on fuel.

Full Hybrid

One of the characteristics of the full-hybrid concept that the vehicle can pull away from rest and drive without the combustion engine turning over. Full-hybrid systems use high-voltage accumulators with voltages ranging from approximately 100 V to in some cases well in excess of 200 V. In a configuration of this nature the electric motor is easily capable of overcoming inertia to set the car in motion, and when sharp acceleration is called for the torque of the combustion engine and that of the electric motor are used in parallel. This is the mode known as boost.

Principles of Hybrid Technology.

Write the missing data.

	Power of electric motor	Voltage range	Possible functions	Fuel savings
Micro-hybrid	2 to 3 kW	12 V		Less than 10%
Mild-hybrid			Start/stop functions Boost functions Energy recovery	
Full-hybrid				More than 20%

Classification by Drive-unit Configuration

In terms of drive-unit configuration, hybrid cars can be classified as belonging to one of four groups:

- Serial hybrid
- Parallel hybrid
- Power-split hybrid
- Plug-in hybrid

Serial Hybrid

A serial-hybrid car has an electric motor and a combustion engine. The characteristic of this concept is that only the electric motor acts directly on the driven wheels.

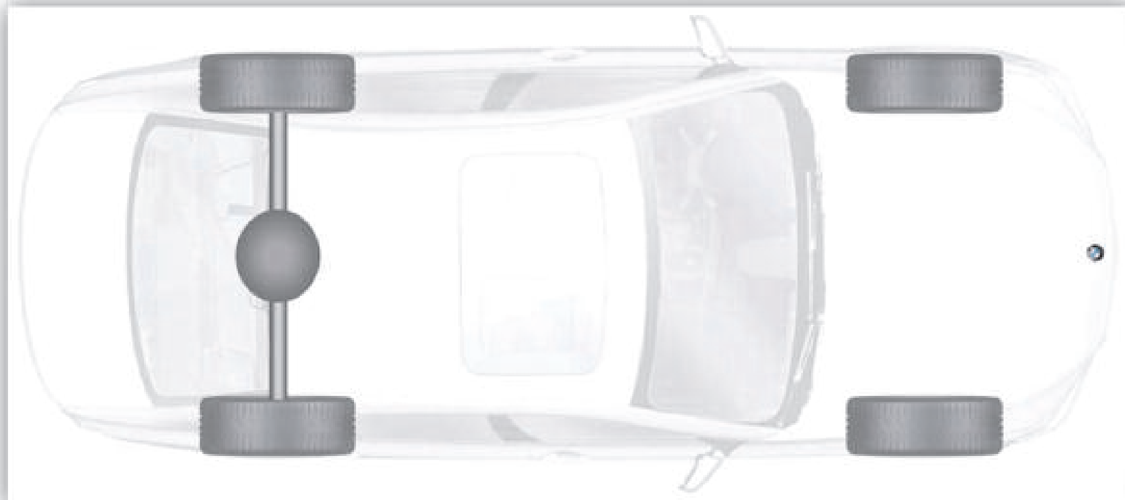
The components in the powertrain are arranged one after the other and this is why the configuration is termed serial. The combustion engine drives an alternator that generates the energy for the electrical propulsion unit and for charging the battery. The flow of electrical energy is controlled by the power electronics.

The size of the alternator and the electric accumulator (the battery, in other words) depends on the operating-mode and charging strategy, range and performance. The need for an extra alternator adds complexity to the design, but this is compensated to some extent by the absence of a gearbox.

A serial-hybrid configuration offers a great deal of flexibility in terms of the positioning of the individual components. The single most telling drawback of the serial-hybrid concept is the double transformation of energy and the diminished efficiency this inherently entails. Combustion engine and alternator both have to be designed for maximum propulsive power. By comparison with parallel hybrids, the combustion engine is more powerful, but it therefore produces more emissions and has a higher fuel consumption.

Fully electric drives are similar to serial drives to some extent. Instead of being inside the vehicle, however, the generator is external. The battery is recharged from the public grid or a private source to which the vehicle is connected while not in use.

Draw in the components of a serial-hybrid drive.



What are the features of a serial-hybrid drive:

Advantages:

Disadvantages:

Parallel Hybrid

Unlike serial hybrids, parallel hybrid systems have both the combustion engine and the electric motor mechanically connected to the driven wheels.

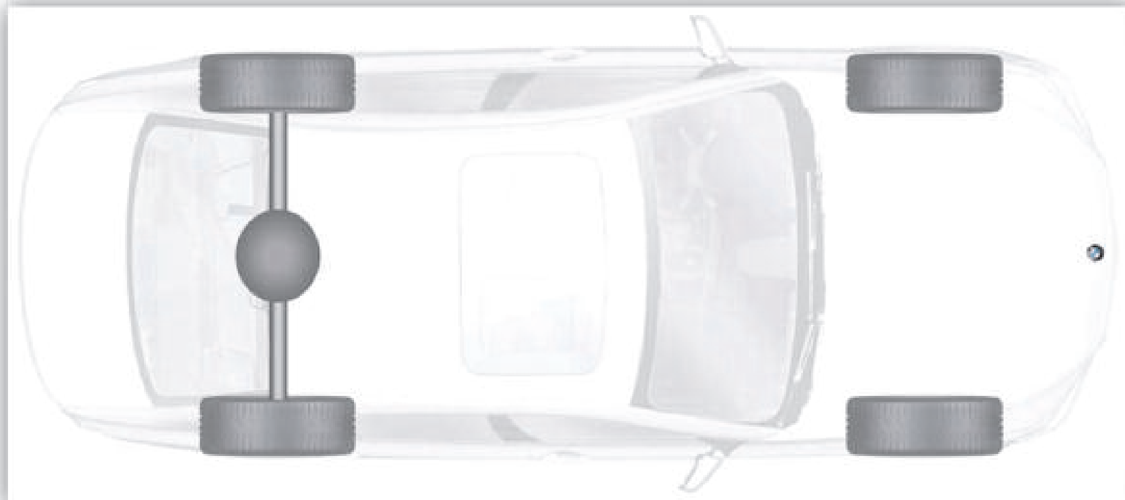
The two propulsion systems can be used either separately or together to propel the car. The introduction of force from the two sources to the powertrain is parallel, hence the term 'parallel-hybrid system'.

Both electric motor and combustion engine can be made smaller and lighter, because the power of both is combined. Savings are the net result, for example in terms of weight, fuel consumption and CO_2 emissions.

An option open to designers looking to maximize performance is to install a full-size, full-power combustion engine and then utilise the boost available from the electric motor. This approach can also produce a reduction in fuel consumption.

The electric motor can also operate as a generator, which is why the term "electrical machine" is more apt than "electric motor". In overrun phases and when the vehicle brakes, the electrical machine generates electricity which – controlled by the power electronics – is stored in the high-voltage battery so that the car can use less fuel. In terms of production outlay, a cost comparison actually puts parallel hybrids ahead of mild hybrids.

Draw in the components of a parallel-hybrid drive.



What are the features of a parallel-hybrid drive:

Advantages:

Disadvantages:

Power-split Hybrid

Power transmission can be either serial or parallel, so hybrid systems of this nature are referred to as serial-parallel or power-split systems.

Various operating modes are possible and individual modes can be engaged to suit driving conditions:

- Combustion engine drives alternator (electrical machine 1) to charge the high-voltage battery bank.
- Combustion engine drives alternator (electrical machine 1). The electricity generated in this way is used to power electrical machine 2 (serial hybrid).
- Combustion engine is mechanically connected to the input shaft, as are the electrical machines.

Both propulsion units drive the vehicle (parallel hybrid).

In this combined hybrid drive mode a coupling provides the means of switching from one propulsion unit to the other. A vehicle with power-split hybrid drive can be electrically powered up to a certain speed.

The electronics also control the way in which the two propulsion modes are combined to keep the combustion engine operating in its most efficient range. The drawbacks of power-split hybrid drives are the sophisticated electronics needed for drive control and the high costs. Power-split systems are usually implemented as full-hybrid configurations.

Plug-in Hybrid

Plug-in hybrids are another extended branch of hybrid technology. A plug-in configuration further reduces fuel consumption by having the electrical energy accumulator charged not only by the combustion engine but also off the grid supply when the vehicle is not in use.

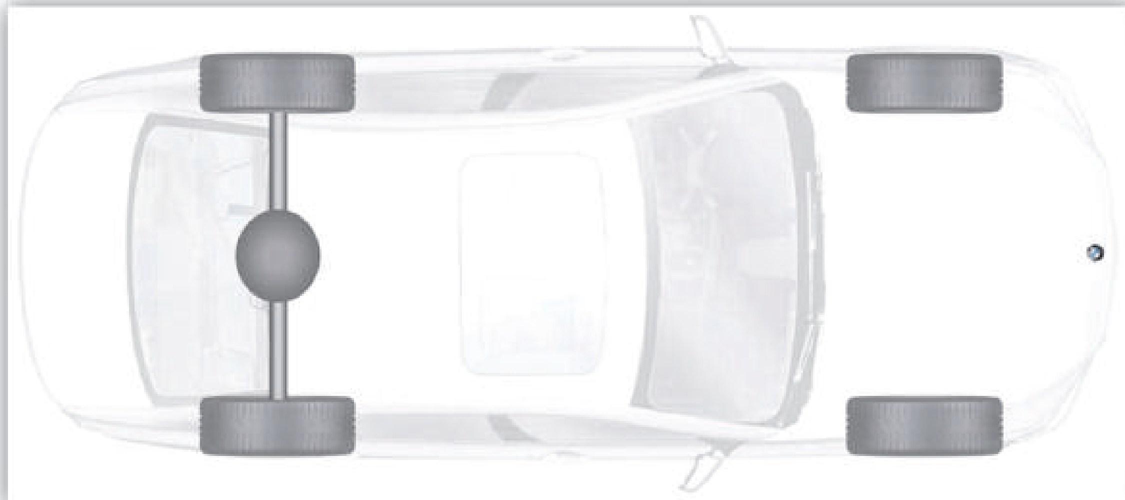
If the battery charge level is sufficient the vehicle can undertake short journeys in zero-emission electrical mode, with the combustion engine in reserve and needed only for lengthy trips or when the battery is drained.

A plug-in hybrid always has a large-capacity battery bank so that more energy from the grid can be stored to make the vehicle less reliant on the combustion engine and maximize the proportion of all-electric driving.

Principles of Hybrid Technology.

Principles and driving situations > Classification by drive unit configuration

Draw in the components of a power-split hybrid drive.



What are the features of a power-split hybrid drive:

Advantages:

Disadvantages:

Driving Conditions

The driving conditions that can apply in the case of a full-hybrid configuration are shown below. The corresponding driving conditions for other hybrid vehicles can be derived by analogy from this summary.

Start/stop Function

When the vehicle is at a standstill with the combustion engine at its operating temperature, for example because the traffic has been held up at traffic lights, the combustion engine is switched off.

This means that the engine is not emitting CO2 and fuel consumption is reduced. While the car is at a standstill the high-voltage battery supplies power for climate control, vehicle lights etc. If the charge state of the high-voltage battery is not sufficient to cover these loads the combustion engine is started to charge the high-voltage battery off the electrical machine and provide enough electrical energy to power the various consumers. When the brakes are applied on the approach to traffic lights, the combustion engine is switched off even before the car comes to a complete standstill (when the car slows to a certain defined speed).

Pullaway

The ability of the electric propulsion unit to deliver high torque at low speed is utilized for pullaway from rest. The car accelerates solely under electric power, with the electric motors drawing the energy they need from the high-voltage battery. The combustion engine remains switched off (engine at operating temperature).

Accelerating (boost function)

When sharp acceleration is needed to lift the car away from rest at a junction, to overcome a steep gradient or to pass slower traffic, if the high-voltage battery is sufficiently charged its power can be tapped and the additional force made available as kinetic energy through the electrical machine. This is known as the boost function. Combining the power output of the combustion engine and the electric motors produce driving dynamics and acceleration similar to those of a vehicle with a more powerful engine.

Steady Driving

The combustion engine and the electrical machine can both contribute to propulsion; the extent to which power is drawn from either source depends on the vehicle's speed and the battery's state of charge at a given time.

Combustion engines do not operate at maximum efficiency when required to propel the vehicle at low to medium speeds. The electrical machine, in contrast, is capable of delivering full torque at very low rpm. If the high-voltage battery is adequately charged, the vehicle is driven solely on electrical energy. The combustion engine is not switched on frequently unless the charge level of the high-voltage battery is low: Under these circumstances some power is tapped from the engine to recharge the battery.

A combustion engine can operate at maximum efficiency when the car is being driven at a steady, relatively high speed. At this end of the performance band the electrical machine would have to draw too much energy from the high-voltage battery. Consequently, the combustion engine is the primary mover for driving under these conditions. If the high-voltage battery is in a low state of charge part of the power developed by the combustion engine is used to recharge the battery through the electrical machine.

Braking

The ability to utilize the energy that would otherwise be shed on descents or wasted when the car is decelerating is one of the main advantages of a hybrid drive.

This mode is known as energy recuperation or more frequently energy recovery. Instead of being dissipated by conversion into thermal energy at the wheel brakes, excess energy is converted into electrical energy by the electrical machine operating as a generator, and stored in the high-voltage battery.

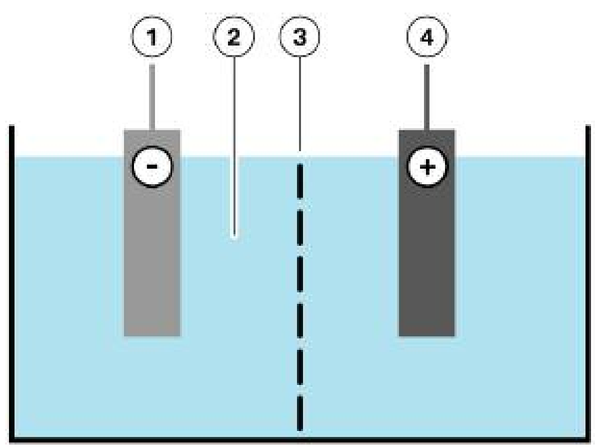
What are the driving situations of a full-hybrid vehicle?

Energy Storage Devices

The energy storage device stores accumulated energy so that it will be available for use when needed at some subsequent point in time. Energy is often converted from one form to another so that it can be stored and it then has to be converted again when needed; this process of conversion is unavoidable in order to minimize losses during stoppages. For example, chemical energy (fuel) is stored in the fuel tank and subsequently converted into thermal and mechanical energy by the combustion engine.

Losses invariably occur in any process of energy storage or energy transformation. There are many kinds of energy-storage devices (mechanical, thermal, chemical, magnetic and electrostatic). Chemical and electrostatic storage devices are explained in more detail below, because these are the types of storage device most frequently used as the secondary source of energy in modern hybrid cars.

Basic structure of a galvanic cell



Index	Explanation	Index	Explanation
1	Negative electrode	3	Separator
2	Electrolyte	4	Positive electrode

Physical Principles of Chemical Storage

Broadly speaking, a galvanic cell consists of the electrolyte, the battery housing and of course the two electrodes. A separator through which ions can pass but which holds back electrons forms an additional insulating barrier between the electrodes. Chemical reactions that take place in the galvanic cell produce an electron excess at one electrode and an electron deficit at the other. Consequently, there is an electric potential - a voltage, in other words - between the two electrodes.

As the battery discharges, therefore, the chemical reaction converts the energy stored in chemical form to change into electrical energy. The reaction that supplies energy is known as discharge and consists of two sub-reactions (electrode reactions) which, although separate in space, are interlinked.

The electrode at which the corresponding sub-reaction takes place at a lower ORP (oxygen-reduction potential) than the other electrode is the negative electrode; the other is the positive electrode. As the cell discharges an oxidation process takes place at the negative electrode and electrons are released; at the same time at the positive electrode the corresponding electrons are absorbed in equal numbers by a reduction process. The electronic current flows through an external consumer circuit from the negative to the positive electrode. Inside the cell the current is carried between the electrodes by ions in the ion-conductive electrolyte (ion current), and ion and electronic reactions in/at the electrodes are interlinked.

Galvanic cells are DC voltage sources. The name indicating the type of galvanic cell is generally derived from the combination of electrode materials. The chemical make-up of the electrolyte and the electrode materials changes, depending on the charge state of the cell. The type of material from which the electrodes are made determines the rated voltage of the cell.

What we generally term a "battery" usually consists of an array of galvanic cells interconnected in such a way as to be usable as an energy source. Technically a AA “battery” is a galvanic cell.

What is the difference between a galvanic cell and a battery?

Draw a circuit of gavanic cells for a higher voltage of battery.

Draw a circuit of gavanic cells for higher capacity of battery.

Capacity

Connecting galvanic cells in parallel produces a battery with a higher capacity. The voltage of the battery is equal to that of a single cell.

Capacity is the electrical charge stored in the battery. A battery's capacity is stated in ampere-hours (Ah). The actual usable capacity (the current that can be drawn from the battery, in other words) depends on the conditions of discharge. An increase in discharge current means a corresponding decrease in usable capacity.

Power

The power of a battery is stated in watts (W) and is the product of discharge current and discharge voltage. It is not usual to state the energy stored in a battery, but energy per unit of mass or unit of volume is nonetheless an important parameter of battery systems.

Energy density is a measure of the distribution of energy over the mass of a substance and is stated in watt-hours per kilogram (Wh/kg). The energy density of the battery used in a hybrid car is crucial in terms of the range the vehicle is able to cover before the battery has to be recharged.

The power density of a battery defines the battery's electrical power as a function of mass and is stated in watts per kilogram (W/kg).

Imagine you are an engineer at the FIZ and are responsible for the development of batteries for hybrid vehicles.

Write several characteristics for the perfect hybrid-battery.

____

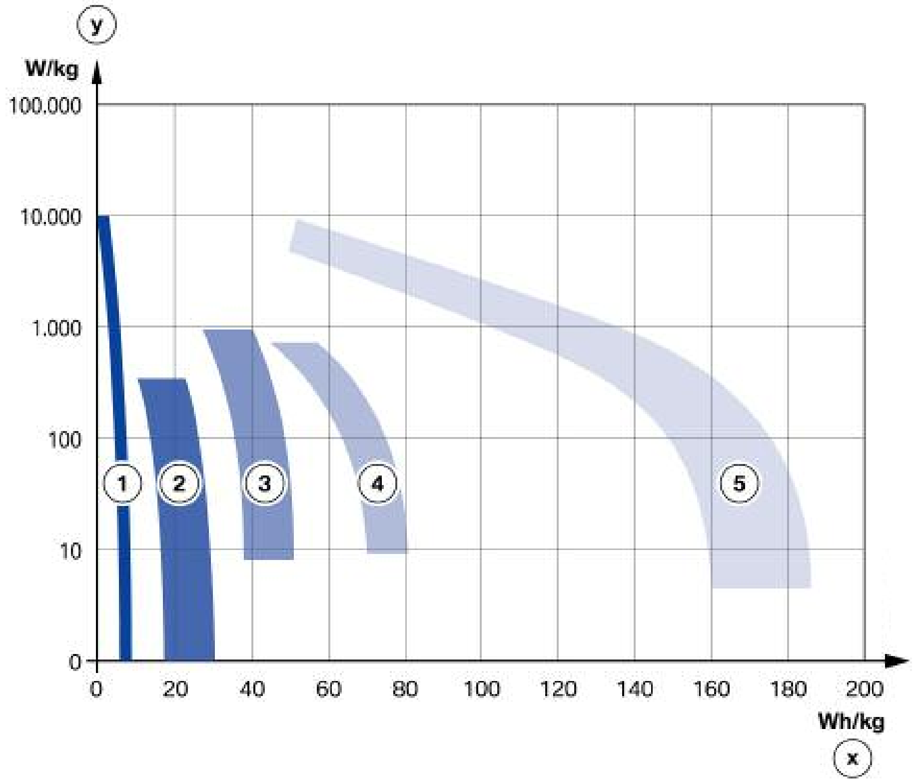
The graph below shows the power density and the energy density of various devices capable of storing electrical energy.

As the graph shows, double-layer capacitors manifest a very high power density but a very low energy density by comparison with other storage devices, so they are able to discharge a very high power over a short period of time.

A comparison of nickel cadmium and nickel metal hydride batteries shows that both have about the same power density, but the nickel metal hydride battery has almost twice the energy density. This in turn means that of two batteries capable of storing the same amount of energy, a nickel metal hydride battery would weigh only half as much as a nickel-cadmium battery.

Translated into terms of range, a car with a nickel metal hydride battery would be able to travel twice as far as a car fitted with a nickel-cadmium battery of the same size.

Energy Density and Power Density of a Battery



Index	Explanation
1	Double-layer capacitor
2	Lead-acid battery
3	Nickel-cadmium battery
4	Nickel metal hydride battery
5	Lithium-ion battery
x	Energy density in Wh/kg
y	Power density in W/kg

Battery Types

Lead Acid Battery

The lead-acid battery is one of the oldest kind of battery systems (lead acid batteries have been around since 1850), but even today batteries of this kind supply electrical energy for millions of motor vehicles. Lead-acid batteries are commonly used as starter batteries for the combustion engines of motor vehicles. Over a limited period of time, batteries of this kind are also capable of supplying power to on-board electrical consumers even when the combustion engine is not running.

The cells consist primarily of positive and negative electrodes and the separators, plus the requisite structural components. Each cell supplies a voltage of two volts. Six cells connected in series deliver the battery voltage of 12 V. The energy density of a lead-acid battery is typically in the order of 30 Wh/kg.

Nickel-cadmium Battery

Nickel-cadmium batteries (NiCd) were first developed more than 100 years ago and the technology is still in use today. An important difference between lead-acid batteries and nickel-cadmium batteries is that in the latter the electrolyte remains unchanged through the charge/discharge cycle. The electrodes of a fully charged nickel cadmium cell consist of plates charged with cadmium at the negative terminal and nickel-hydroxide at the positive terminal. The electrolyte is potassium hydroxide. This combination supplies a voltage of 1.2 V. Energy density is comparable to that of a lead-acid battery.

Cadmium is a heavy metal and is classified as an environmentally hazardous substance and these batteries suffer from what is commonly known as the memory effect - two reasons why NiCd batteries have recently been supplanted by new battery systems. The memory effect is the characteristic loss of capacity that occurs when a nickel-cadmium battery is frequently recharged after being only partly discharged.

The battery gives the impression of "remembering" the energy levels it reached in previous discharge cycles. Instead of the original nominal amount of energy, the battery outputs only this lower amount of energy and the voltage drops.

Nickel Metal Hydride Battery

The nickel metal hydride battery (NiMH battery) is often considered the successor to the NiCd battery.

An NiMH battery cell has nominal voltage of 1.2 volts. The energy density of an NiMH battery is about 80 Wh/kg, so it is twice that of an NiCd battery. NiMH batteries are virtually free of the memory effect described above. They are capable of releasing their stored electrical energy within a very short time with no more than a negligible tailing off in voltage level.

NiMH batteries are easily damaged by overcharging, total discharge, overheating and reversed polarity.

They are also sensitive to changes in temperature. As soon as ambient temperature dips close to the freezing point these batteries evince a significant drop in capacity.

The anode consists of a metal alloy that can reversibly store hydrogen in its crystal lattice to form a metal hydride. The electrolyte is a 20% solution of potassium hydroxide, which also surrounds the nickel-hydroxide cathode.

As the battery discharges the hydrogen oxidizes; this chemical process produces a potential of 1.32 volts at the two electrodes. In order to prevent the metal from oxidizing instead of the hydrogen as the battery approaches the end of its discharge cycle, the negative electrode is much larger than the positive electrode.

What are the characteristics of the Nickel Metal Hydride Battery?

Lithium-ion Battery (Li-ion battery)
In the 1960s, researchers were starting to look at lithium batteries with lithium-metal anodes and nonaqueous electrolytes. The non-rechargeable lithium batteries were initially used in space exploration and for military purposes. Low self-discharge is a feature of batteries of this kind and for this reason they are still used even today in cardiac pacemakers, clocks and cameras. Rechargeable lithium batteries made their commercial breakthrough with the market launch of a cell that dispensed entirely with metallic lithium; this was the Lithium-ion battery.

Today, Lithium-ion batteries are the preferred energy source for portable devices with high energy demand (mobile phones, digital cameras, notebook computers, etc.). Their high energy density also makes them attractive for use in electrically powered and hybrid vehicles. Additional benefits are the ability to supply a constant voltage across the entire discharge period cycle and the fact that they do not suffer from a memory effect.

Most Li-ion cells have a positive electrode made of lithium-metal oxides built up in layers (e.g. LiCoO2 or LiNiO2). The negative electrode consists of layers of graphite. The two electrodes are in a nonaqueous electrolyte. There is a separator between the two electrodes.

The Lithium-ion cells generate a source voltage by the movement of lithium-ions. When the cell is charging, positive lithium-ions migrate through the electrolyte from the anode and insert themselves into the graphite layers of the cathode. The lithium-ions combine with the graphite (carbon) without destroying the graphite's molecular structure. As the cell discharges the lithium-ions extract from the graphite and move back to the metal oxide and the electrons can flow through the external circuit to the positive electrode. The lithium-ions cannot combine with the graphite of the cathode in the process known as intercalation unless the negative electrode has a protective coating through which the small lithium-ions can pass, but that constitutes an impermeable barrier to molecules in the electrolyte.

Lithium-ion batteries have a low self-discharge rate and their efficiency is approximately 96%, due primarily to the high migration capability of lithium-ions. Efficiency is affected by temperature and drops off sharply at low temperatures.

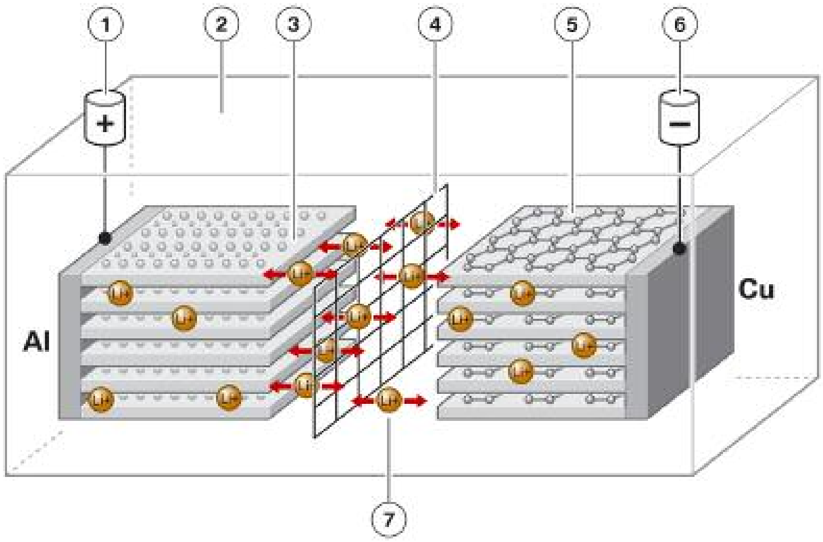
A conventional Lithium-ion cell supplies a nominal voltage of 3.6 V. The tension of a Lithium-ion cell, therefore, is three times that of a nickel metal hydride battery. Total discharge to below 2.4 V causes irreversible damage and loss of capacity to the cell, so it is essential to ensure that this threshold is not reached.

Specific power density is in the range from 300 to 1500 W/kg. Energy density is about twice that of a nickel-cadmium battery, about 95 to 190 Wh/kg.

Lithium-ion batteries should not be discharged below 40%, because at lower levels significant loss of capacity can occur due to irreversible reactions in the electrodes. Another aspect is that the higher the cell voltage, the more rapid the aging process in batteries of this kind. Consequently, it is best to avoid keeping Lithium-ion batteries constantly 100% charged. The optimum state of charge is in the range between 50% and 80%.

Mechanical damage can short the cell. The high current level would melt the casing and cause the cell to catch fire. Li-ion batteries should not be immersed in water. Lithium-ion cells manifest a severe reaction to water, particularly when they are fully charged. If a battery of this kind catches fire it is important not to attempt to extinguish it with water: smother the fire with an inert substance such as sand, for example.

Each battery is an array consisting of many individual cells, so each cell has to be individually monitored. This is precisely what the battery management system is designed to do. This system ensures that the individual cells are not overcharged and not discharged too severely, and it also balances charge over individual cells, if necessary.



Index	Explanation
1	Positive electrode
2	Housing with electrolyte
3	Lithium-metal oxide
4	Separator
5	Graphite layer
6	Negative electrode
7	Lithium-ion

What are the characteristics of the Lithium-ion battery?

Double-layer Capacitors

The principle of the double-layer capacitor was discovered in 1856 by German physicist Hermann von Helmholtz. He described the make-up of double layers of charge carriers forming on electrodes contained in an electrolyte when a voltage is applied from an external source. Today's double-layer capacitors are marketed under many different names (the names vary from manufacturer to manufacturer), including for example; Goldcaps, Supercaps, Boost Caps and Ultracaps.

A double-layer capacitor is an electrostatic energy storage device for electrical energy with a very high power density of up to 10 kW/kg, but an energy density of about 5 Wh/kg, which is low by comparison with chemical storage devices. The advantages of a double-layer capacitor are its very high efficiency (approaching 100%), its low self-discharge rate and its durability. These devices, moreover, are completely free of the memory effect. The inherently low energy density renders double-layer capacitors unsuitable for use as sole energy accumulators for vehicle propulsion, but in combination with chemical storage devices the weight savings are considerable and an additional benefit is that the chemical accumulators have an extended service life.

Capacity depends on the thickness of the insulating layer and the surface area of the electrodes.

The high power density of double-layer capacitors is due to the very thin insulating layer and the large surface area of the electrodes. Activated carbon is used to produce electrodes with this very large surface area. Activated carbon is fine-grade carbon with a very large inner surface (300 to 3000 m2/g). 4 grams of activated carbon aggregate to an inner surface is roughly equal to the surface area of a football field. The insulating layer is only a few nanometers thick.

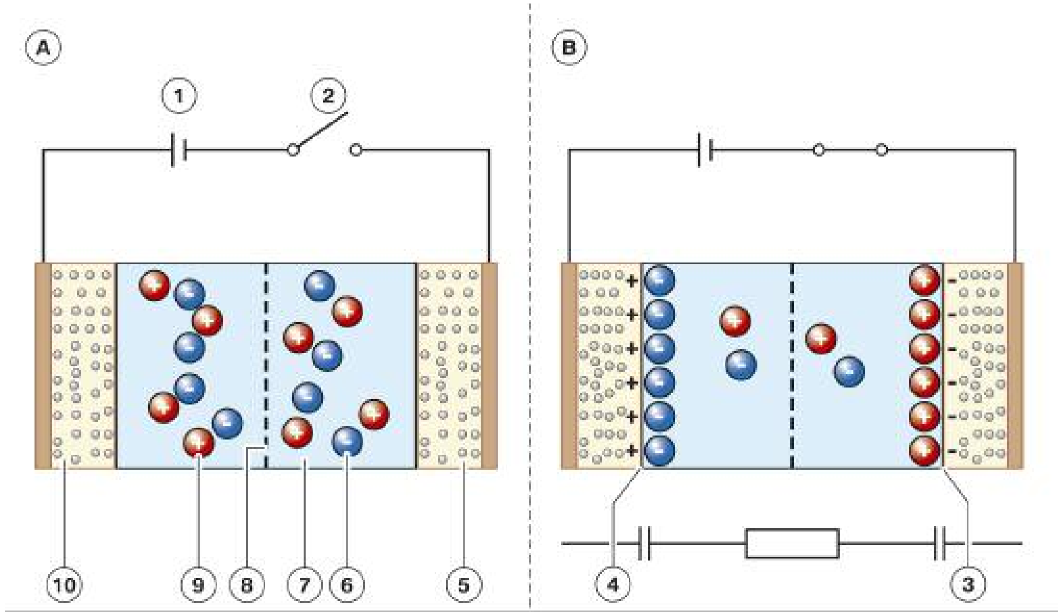
The capacity of double-layer capacitors is in the range from 1 to 50 farads and dielectric strength is about 2.5 V. As is the case with chemical accumulators, capacity and operating voltage can be increased by connecting multiple capacitors in series or in parallel.

Summary

As we have seen, the galvanic cell is the heart of any useful energy-storage system. Consequently, selecting a cell of suitable type is of crucial importance in terms of the system's ability to store and provide energy. The table below is an overview of the properties of the mainstream electrical energy-storage devices.

If voltage and/or capacity of the cell is not sufficient for a given application, multiple cells can be connected in series or in parallel, respectively.

Device	Cell Voltage (V)	Power Density (W/kg)	Energy Density (Wh/kg)	Memory Effect	Operating Temperature (°C)
Lead Acid	2	5	30	-	Up to 45
NiCd	1.2	6	40	Yes	Up to 65
NiMH	1.2	7	80	Low	Up to 60
Li-ion	3.6	8	95 - 190	No	Up to 50
Double Layer Capacitor	2.3 - 2.7	9	5	No	Up to 65

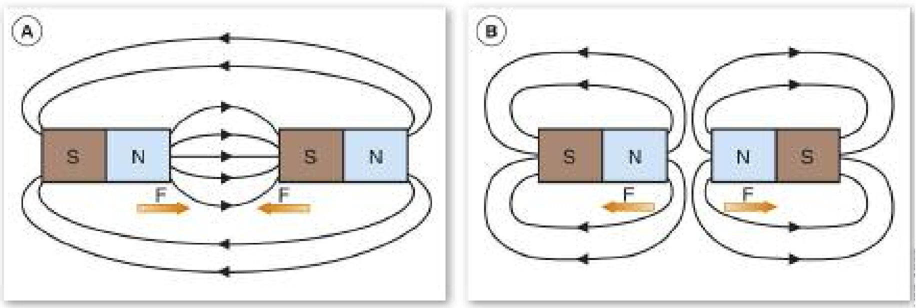


Index	Explanation
A	Double-layer capacitor is discharged
B	Double-layer capacitor is charged
1	Voltage source
2	Switch
3	Insulating charge-carrier layer
4	Insulating charge-carrier layer
5	Negative electrode
6	Negative charge carriers
7	Electrolyte
8	Separator
9	Positive charge carriers
10	Positive electrode

Electrical Principles

Magnet

A permanent magnet (a magnet made from what is termed a magnetically "hard" material) is usually made of an alloy primarily of iron and often containing cobalt or nickel. It is magnetized in the process of production and it retains this magnetism permanently, hence the name. Permanent magnets are used for a wide variety of purposes, including that of generating energizing fields in fractional-horsepower electric motors.

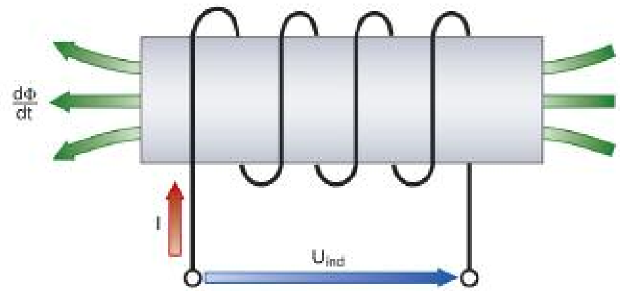


Index	Explanation
A	Opposite magnetic poles are mutually attractive
B	Like magnetic poles repel

Electromagnet

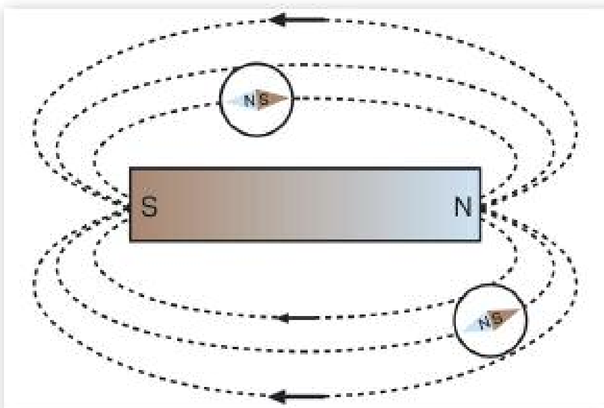
A coil carrying an electric current generates a magnetic field very similar to that of a bar magnet. Consequently, it can be used as an electromagnet. Unlike the magnetism of a permanent magnet, this magnetism can be switched on and off, because it occurs only while current is flowing through the coil.

In direct current motors with electric excitation such as series-wound or shunt-wound motors, electromagnets are used to generate the magnetic field in the stator. Electromagnets are also used for the coils in relays.



Index	Explanation
Φ	Magnetic flux
I	Current through coil

Magnetic Field
A magnetic field can be generated with the aid of a permanent magnet or an electromagnet. The magnetic fields can be visualized as magnetic field lines running from the magnet's north pole to its south pole. The stronger the magnetic field, the more densely packed are the magnetic field lines in the diagram.



Faraday's Law of Induction
Electromagnetic induction was discovered in 1831 by Michael Faraday. Electromagnetic induction is one of the basic phenomena of electrophysics. Faraday's law of induction describes a relationship between magnetic fields and electrical voltages and is crucial to our understanding of how electrical machines work.

The law of induction states that a Uind will be induced by the reversing magnetic flux flowing through a coil with the number of turns N. This relationship can be expressed as: Uind = N • /dt.

Even in a magnetic field without a time rate of change a voltage is induced in the coil if the coil itself is moved inside the magnetic field. Induction is utilised primarily in electrical machines such as generators, electric motors and transformers. The direction of flux of the induced voltage can be determined by application of Lenz's law: the direction of flux of the induced current is always in such a direction as to oppose the motion or change causing it.

If the current flowing through the coil changes in intensity, its magnetic field also changes and induces in the coil a voltage that is opposite the change in current direction causing it. This is generally termed self-induction. The faster the magnetic field changes and the stronger the changes, the higher is the resultant induction voltage.

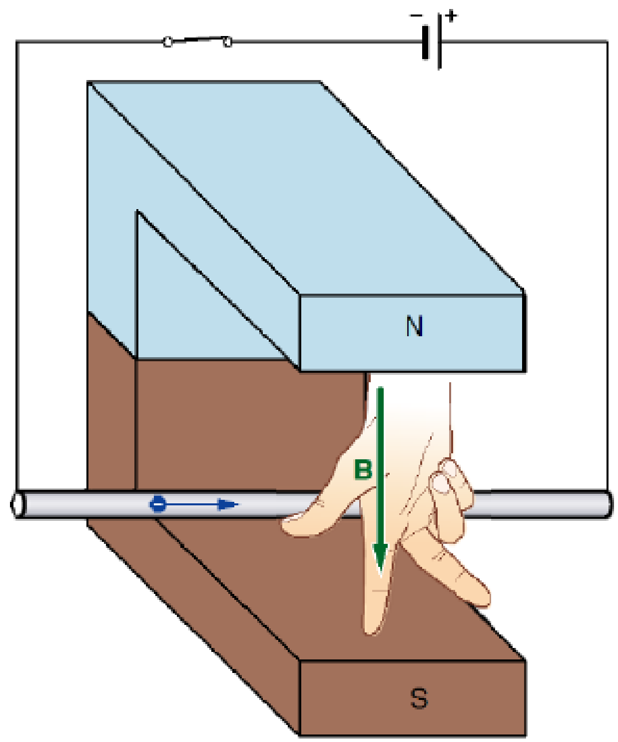
Lorentz Force

The force known to physics as the Lorentz force is the force that a magnetic field exercises on a moved electrical charge. A force F acts on the electrons in the conductor, causing the entire conductor to move in one direction. The orientation of the vectoring force can be determined by the "right-hand rule" or by the principle of cause/agent/effect. Applied to the graphic above, this means:

Cause = current —> agent = magnetic field —> effect = force on electrons

Fill in the rest of the labels in the diagram to the right:

Lorentz force acting on an electron



Index	Explanation
1	Electron
B	Magnetic flux direction
F	Force acting on an electron
I	Electric current
F	Force acting on an electron
N	North pole
S	South pole

Transformers

A transformer consists of two coils around a common iron core. There is no conductive connection between the two coils, in other words they are galvanically insulated from each other.

If an alternating current is applied to one of the coils, the law of induction requires that an alternating current will be induced in the second coil. A voltage can then be measured between the ends of the second coil. The strength of the induced voltage depends on the primary voltage and the number of turns in the two coils.

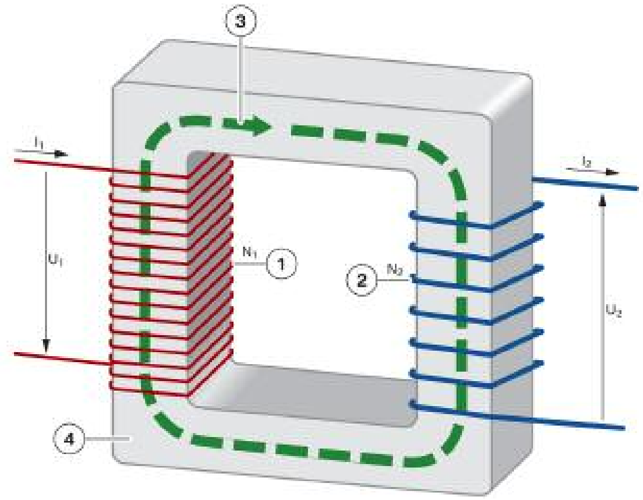
U1/U2 = N1/N2

If the primary and secondary coils have the same number of turns, secondary voltage U2 will be equal to primary voltage U1. If the secondary coil has twice as many turns as the primary coil, the secondary voltage will be twice the primary voltage. A load connected to the secondary coil draws energy from the circuit that has to be made up for on the primary side. In an ideal (imaginary) transformer, the energy input on the primary side is equal to the energy tapped on the secondary side, in other words an ideal transformer is loss-free. The currents I1 and I2 are inversely proportional to the voltages, because in this ideal transformer power is equal on the primary and secondary sides.

U1 (I1) = U2 (I2)

Ideal transformers, however, do not exist in the real world, because losses always occur. Every transformer, therefore, outputs less electrical energy than it receives. The losses in electrical energy are partly the result of heat generated in the coils on account of electrical resistance and partly the result of what are known as eddy currents. The eddy currents can be minimized by using a transformer core made up of a large number of thin iron sheets instead of a solid-iron core. These sheets of iron are insulated by a lacquer coating and this arrangement interrupts the flux of eddy currents.

Structure of a transformer



Index	Explanation
1	Primary coil with number of turns N1
2	Secondary coil with number of turns N2
3	Magnetic flux
4	Iron core

Given the following values, calculate the voltage and current of the second coil.

N1 = 80 number of turns

U1 = 40 Volts

I1 = .5 Amps

N2 = 20 number of turns

U2 = __________ Volts

I2 = ___________ Amps

Electrical Machines

Electrical machines are devices capable of converting electrical energy into mechanical movement and mechanical movement into electrical energy. Depending on how the energy is transformed, we talk about electric motors (electrical to mechanical), or generators (mechanical to electrical). All electrical machines make use of the fact that like magnetic poles repel and opposite magnetic poles attract.

At least one of the magnetic fields is produced by an electric current. Electrical machines can also be classified by type of current, for example direct current (DC), alternating current(AC) or rotary current (more commonly called three-phase current) machines, or by the operating principle, which gives us the classifications of synchronous or asynchronous machines.

Out of all these various classifications, the following electrical machines are discussed in more detail below:

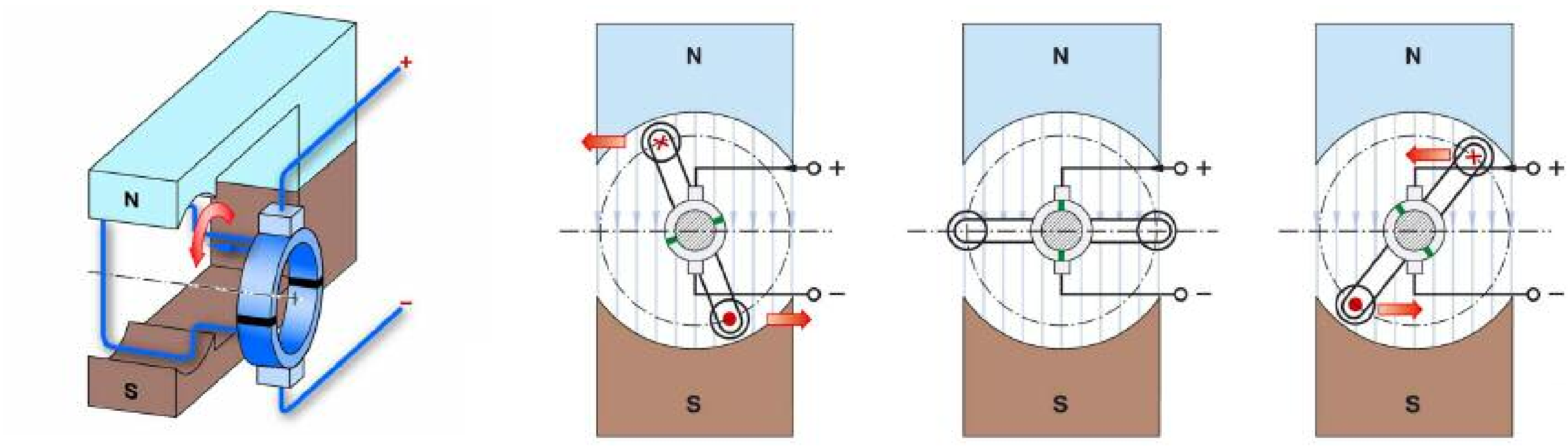
- Direct-current machines
- Synchronous machines
- Asynchronous machines.

Direct-current Machines

Direct-current machines were the earliest electromechanical converters, primarily because of historic development and the availability of electrical energy in the form of direct current from galvanic cells.

The first direct-current machine was built in about 1830. The introduction of rotary current (three phase current) in 1890 or thereabouts meant that the DC machine was ultimately supplanted by the synchronous machine. Even today, however, direct-current machine designs are still with us and are used in a very wide range of applications. Direct-current motors with rating up to about 100 Watts are used in huge numbers in vehicle electrical systems as motors for wipers, power window lifters and blowers and as servomotors.

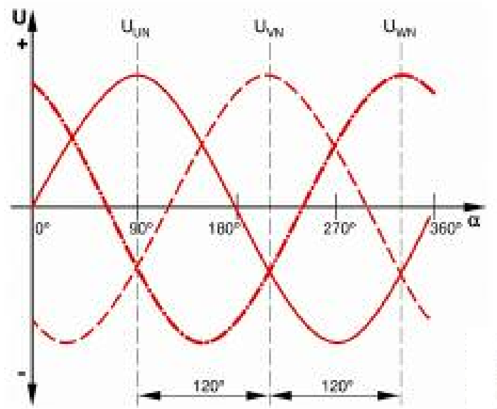
Explain the operation of a direct current machine in your own words.

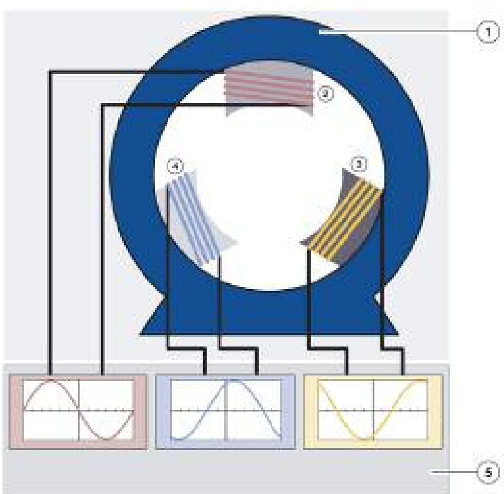


Rotary-current (three-phase) Machines

Three-phase machines are electromechanical converters that can operate either as motors or as generators.

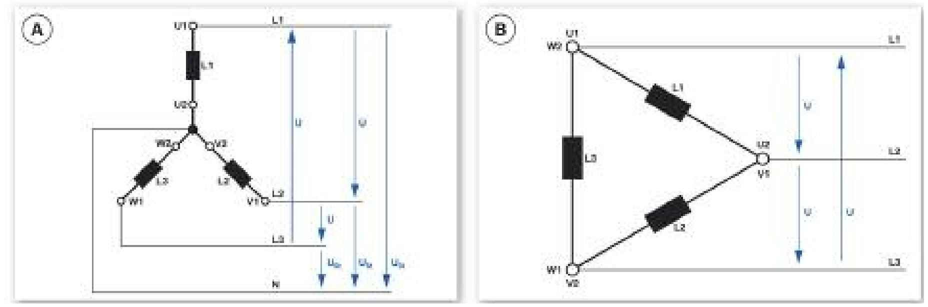
In motor mode the rotating magnetic field is generated by the three-phase rotary current. In generator mode the machine rotary current is an alternating current with three phases (live conductors). The term "rotary current" derives from the mode of generation, but the term "three phase" motor is more common, simply because these machines have three phases.





Index	Explanation
1	Stator
2	Winding U
3	Winding V
4	Winding W
5	Phases of rotary current

Phases of the three alternating voltages



Index	Explanation
A	Star circuit
B	Delta circuit

In a star circuit, leg ends U2, V2 and W2 are all connected to point N. Outer conductors L1, L2 and L3 of the star circuit run from leg starting points U1, V1 and W1, respectively. In a delta configuration the start of one coil leg is connected to the end of another coil's leg. Broadly speaking, the coils are all connected one behind the other. Outer conductors L1, L2 and L3 run from the connecting points to the consumer. Because the coils are connected in this way, only three conductors are needed to wire the three phases L1, L2 and L3. In principle, both types of three-phase machine have the same stator structure with a three-leg rotary-current winding.

They differ only in the structure of the rotor. The structure of the rotor is the feature that enables us to distinguish between synchronous and asynchronous machines.

Synchronous Machine

A three-phase synchronous machine is an electromechanical converter that operates with a three phase supply as an electric motor, or as a generator producing a three-phase supply for a consumer.

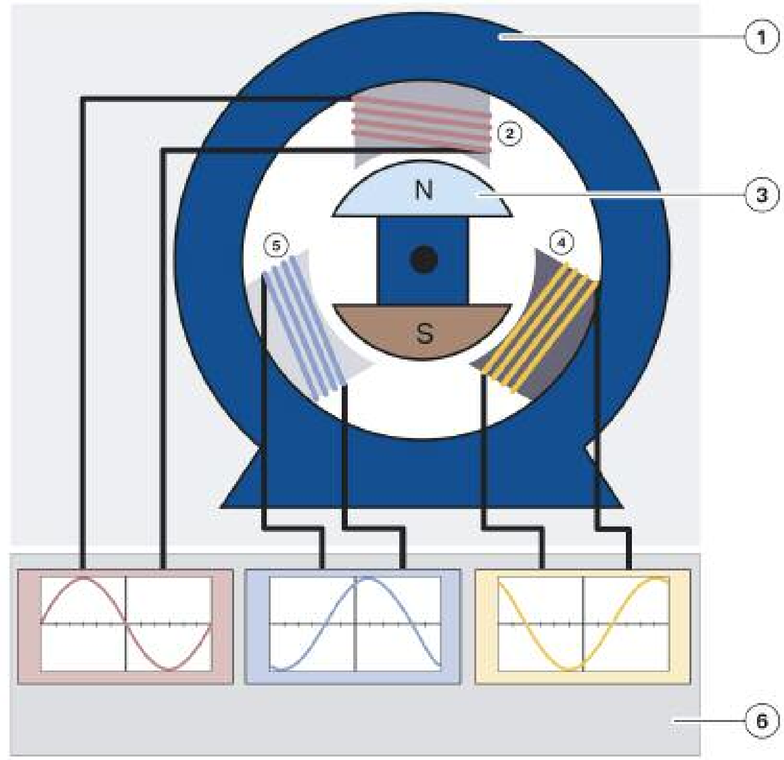
Synchronous machines are used primarily as generators to produce electrical energy in power plants.

A synchronous machine is generally the first choice nowadays as well as the generator in a motor vehicle to supply electrical consumers and charge the battery. In the medium-power range synchronous machines have become rare these days although this is set to change because hybrid-vehicle technology is turning more and more to synchronous machines.

The magnetic field in the rotor of a synchronous machine is generated by permanent magnets (in small-scale machines) or by electromagnets (in larger machines). In the latter case wiper contacts are necessary, but the current flowing through these contacts is comparatively low. Unlike direct-current machines, a synchronous machine does not need a commutator.

Most synchronous machines are of internal-pole design. Some designs have the stator windings inside the machine and the rotor with permanent magnets outside. A machine of this kind is referred to as an external-rotor machine.

Structure of a synchronous machine

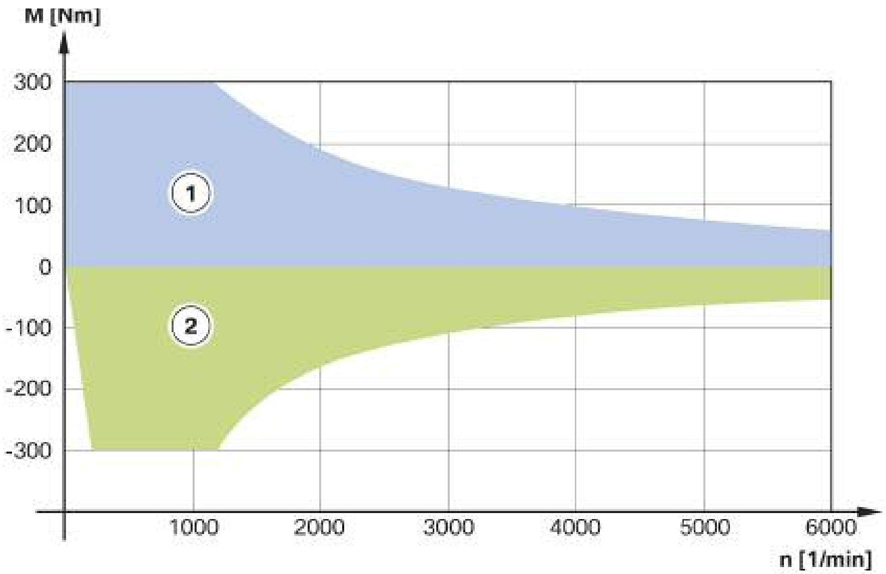


Index	Explanation
1	Stator
2	Winding U
3	Rotor
4	Winding V
5	Winding W
6	Phases of rotary current

Principle of Synchronous Machines

When a rotary current is applied to the windings of the stator, a corresponding rotating magnetic field is generated. The magnetic poles of the rotor follow the direction of the rotating field. This causes the rotor to rotate. The rotor moves at the same speed as the rotating magnetic field. This speed is known as the synchronous speed. Hence the term "synchronous machine". The speed of the synchronous motor is precisely defined by the frequency of the rotary current and the number of pole pairs. A frequency converter has to be used in order to achieve stepless speed control of a synchronous motor.

Synchronous machines do not start up under their own power: they must be set in motion either mechanically or with the aid of frequency converters, accelerated to their rated speed, and synchronized.



Index	Explanation
1	Operation in motor mode
2	Operation in generator mode

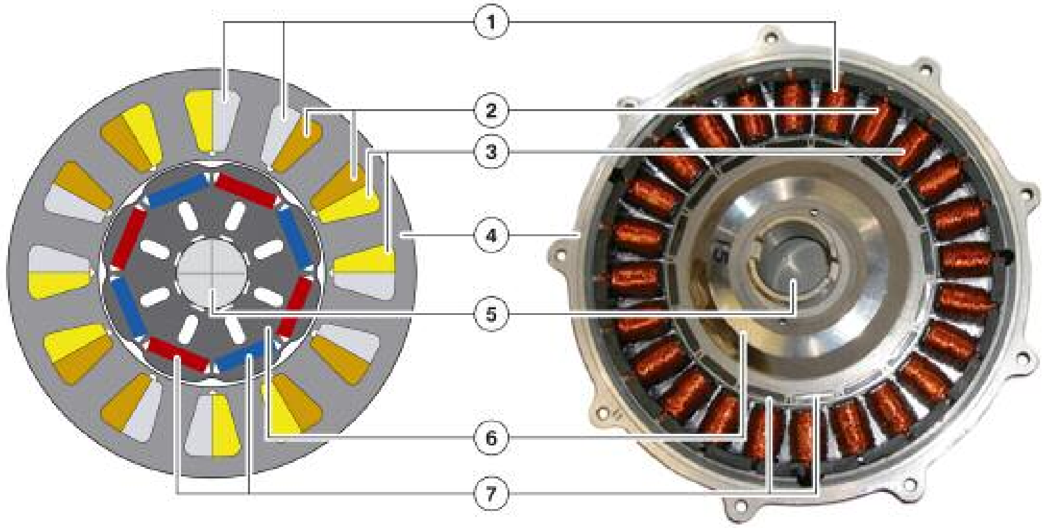
Most of the three-phase machines used in hybrid automotive technology are of the synchronous type.

The permanent magnets generate the magnetic field of the rotor, so it is not necessary to tap energy into the system from outside. This is why these machines have a very high power density, combined with a very high degree of efficiency (> 90%).

Principles of Hybrid Technology.

System components > Electrical machines > Rotary-current (three-phase) machines

Note the parts of a synchronous machine.



Index	Explanation
1	
2	
3	
4	
5	
6	
7	

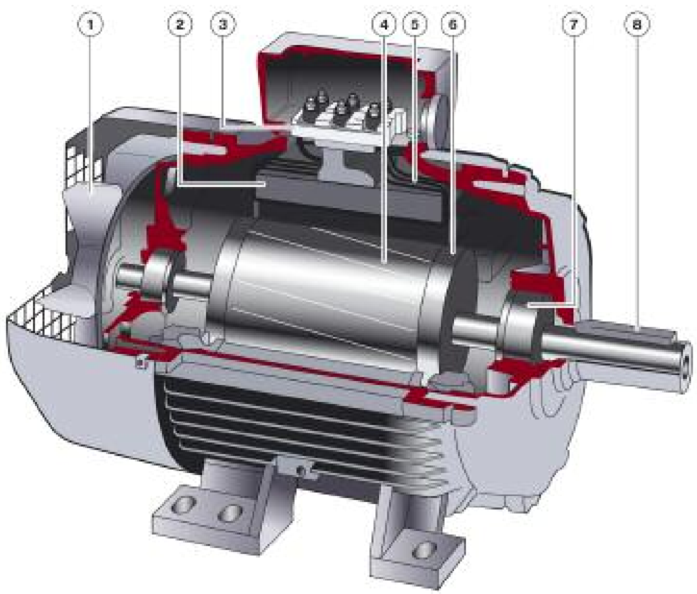
What are the advantages and the disadvantages of a synchronous machine.

Advantages	**Disadvantages**

Asynchronous Machines

A three-phase asynchronous machine can be used as either a motor or a generator. The characteristic feature of an asynchronous machine is that the rotor does not have a direct supply of electricity. The motor's magnetic field is built up by induction from the rotary field of the stator. Another term frequently used for machines of this type is "induction machine", because the current flowing through the rotor is always induced by the rotary field of the stator. The rotor is often shaped like a round cage with bar conductors that make up the cage short-circuited at the ends.

Structure of an asynchronous machine



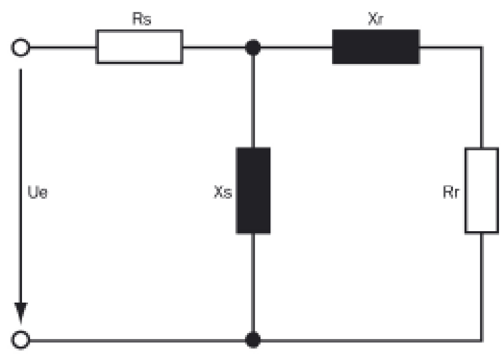
Index	Explanation	Index	Explanation
1	Fan	5	Stator winding
2	Stator sheet pack	6	Short-circuit ring
3	Terminals (line in)	7	Roller bearing
4	Rotor sheet pack with rotor bars	8	Shaft

The rotary field in the stator winding reverses the magnetic flux in the conductor loops of the rotor.

This induces a voltage that causes current to flow in the short-circuited conductor bars. This current generates a magnetic field of its own. Lenz's law states that the direction of flux of the induced current is always in such a direction as to oppose the motion or change causing it. The outcome is a torque that causes the rotor to spin in the direction of the stator's rotary field. Consequently, induction is caused by the difference in the relative speeds of the rotary fields of the stator and the rotor. However, the rotor cannot be permitted to achieve the same speed as the stator's rotary field because under these circumstances the magnetic flux change in the conductor loops would be zero and no voltage would be induced. The difference between the speed of the stator's rotary field and the rotor is known as the slip speed, but it is also referred to as the asynchronous speed. It is dependent on load. Stator field and rotor rotate at different speeds so they are not in synchronization - this is why a machine of this type is referred to as an asynchronous motor. One advantage of asynchronous motors over synchronous designs is that they are inherently much simpler and therefore more robust. This derives primarily from the fact that the principle dispenses with both commutator and brushes. Simplicity of design also makes for lower cost of manufacture and low-maintenance operation. Asynchronous motors are the most commonly used kind of electric motor.

In terms of electrical layout, an asynchronous machine corresponds to a transformer. The stator winding is the primary side and the short-circuited conductor bars are the secondary side. Current settles to a level that is dependent on speed.

Equivalent circuit diagram of an asynchronous motor



Index	Explanation
Ue	Line voltage
Rs	Ohmic resistance of the stator winding
Xs	Inductive resistance of the stator winding
Xr	Inductive resistance of the rotor
Rr	Ohmic resistance of the rotor

Rs and Xs are the most significant features of the equivalent circuit diagram of an idling asynchronous motor, and this is the reason why the input of a machine of this nature is almost entirely reactive power.

As long as the rotor is not in motion, the machine is a transformer with short circuit on the secondary side. This means high currents and powerful magnetic fields. In this pullaway range the machine is not operating efficiently and the motor heats up rapidly and severely. As soon as the armature starts to rotate and adjust to the rotary field in which it is spinning, the currents drop and efficiency improves.

Speed control for asynchronous machines is generally implemented with power electronics and frequency converters and speed varies as frequency is increased or decreased.

Advantages of asynchronous machines:

- Durability
- Low maintenance, because structure is straightforward and brushless
- Comparatively low manufacturing costs
- Self-start capability
- High short-term overload capability
- Inherently robust design.

Disadvantages of asynchronous machines:

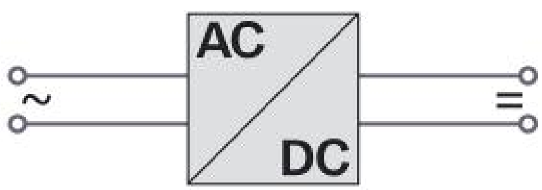
- Less efficient than synchronous machines with permanent magnets and high torque utilization
- Low pullaway torque unless coupled to a frequency converter with run-up control.

Current Inverters

Circuits designed to convert electric energy in terms of the voltage waveform and the voltage and current levels are known as current converters. Distinctions are drawn between rectifiers, inverters and converters (often called transformers).

Rectifiers convert AC voltage to DC voltage. Conversely, a DC voltage can also be changed into an AC voltage. Inverters are used for this purpose. Transforming a DC voltage to a higher or lower DC voltage is a job for a converter. Converters are also more frequently, but not necessarily accurately, called DC/DC transformers. AC converters (also known as AC transformers) are used to transform an AC voltage into a different AC voltage of a different amplitude. Frequency converters are used if the frequency of the AC voltage has to be changed. In hybrid cars the power electronics are used to convert direct current voltage into alternating current voltage and vice versa. Moreover, power electronics are also used for highly flexible adaptation of the operating points of electrical machines.

Rectifiers

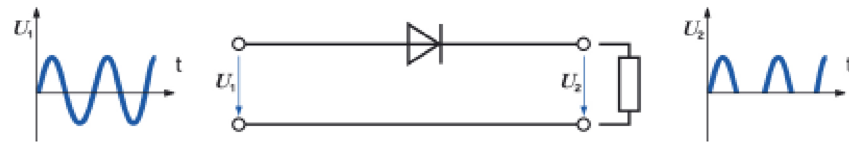


Symbol used in circuit diagrams to represent a rectifier

Rectifiers are used to transform AC voltage into DC voltage. A rectifier consists of multiple diodes arranged in such a way as to function as current rectifiers. The diodes deflect the corresponding half waves of the AC voltage to the same direction, producing a pulsating direct current voltage. In order to obtain true constant-voltage DC, the voltage output by the rectifier has to be smoothed by capacitors or chokes. Rectification can be uncontrolled by semiconductor diodes, or controlled by thyristors.

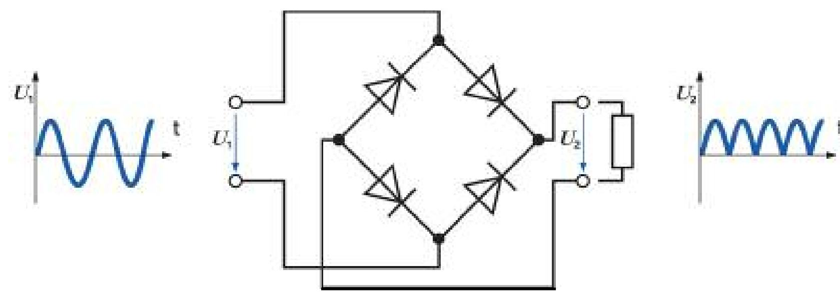
A controlled rectifier needs a control voltage, a trigger that defined the time at which a given electronic switch has to be opened and closed in order to achieve the rectifying effect. Controlled rectifiers are implemented using electronic gates such as thyristors and MOSFETs. An uncontrolled rectifier rectifies the input AC voltage without extra control electronics.

Half-wave Rectifier



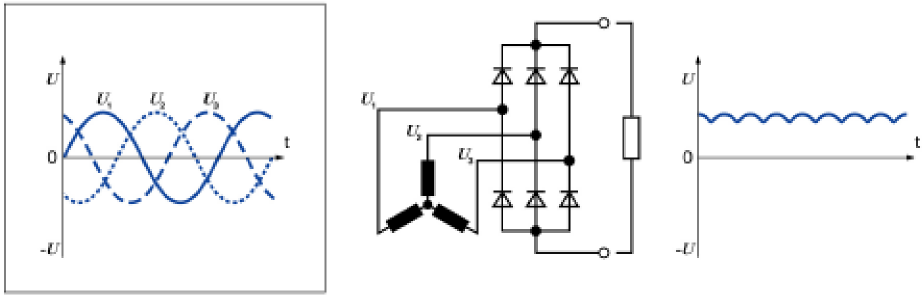
A half-wave rectifier works by allowing one half of each AC wave to pass. The other half wave is blocked. The drawbacks of this circuit are the ripple at its output and the very poor degree of efficiency. The rectified voltage has to be smoothed before it can be used. The ripple is of the same frequency as the input voltage.

Full-wave Rectifier Circuit



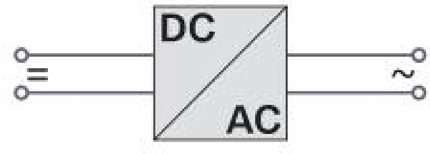
The drawbacks of a half-wave rectifier can be overcome to a large extent by using full-wave rectifiers (also known as bridge rectifiers or - less commonly - two-pulse bridge connections). There are four diodes in the circuit. The AC voltage applied on the left is converted into a pulsating direct current voltage (shown here on the right). This is a full-wave rectifying circuit, so the negative half-wave of the AC voltage always appears as exclusively positive in the DC circuit at consumer R. The ripple frequency is twice that of the input voltage. Similarly, this circuit also has a better degree of efficiency.

Three-phase Full-wave Rectifier



Three-phase current can also be rectified by what is known as a six-pulse bridge circuit. This circuit has six diodes, so all the half-waves of the three phases are used. The rectified direct current voltage evinces no more than slight ripple. In motor vehicles, circuits of this nature are used to rectify the alternator voltage, for example.

Inverters

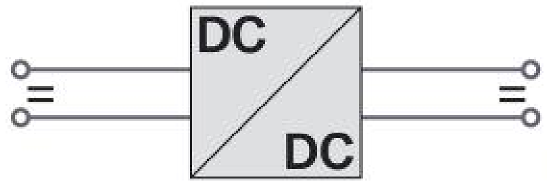


The converters that convert direct current voltage into alternating current voltage are called inverters.

Inverters can be designed to provide single-phase alternating current or three-phase AC. They are capable of very high degrees of efficiency in the region of 98 percent. Inverters are used in situations in which electric consumers need an AC supply in order to operate, but only a DC source is available. In hybrid cards, for example, which store their electrical energy in high-voltage batteries but the electrical machine that provides propulsive power needs three-phase electricity.

Another typical application is in a photovoltaic array. The power from the DC voltage source has to be fed into the AC or three-phase grid.

DC/DC Converter

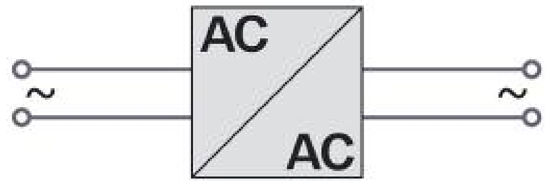


A DC/DC converter (often - though inaccurately - termed a transformer in common parlance) is a converter that converts a constant-current input voltage to a higher or lower DC voltage by periodic switching. DC/DC converters are commonly used in electrical propulsion technology. The basic types are step-down transformers, step-up transformers and inverters. The switches are generally either power MOSFETs or thyristors.

Direct current voltage as such cannot be transformed, so a DC/DC converter works much like an electronic switched-mode power supply, initially transforming the direct current voltage into an AC voltage. This AC voltage then passes through a transformer in which it is stepped up or down, as appropriate, and then transformed back into a direct current voltage and smoothed. On account of the principle involved, current can flow in only one direction through a DC/DC converter.

In mild-hybrid and full-hybrid vehicles a DC/DC converter is needed to step the voltage of the high-voltage battery down to 12 volts. The DC/DC converter is a dual-mode implementation: it has to be bidirectional so that the high-voltage battery can be charged with jump leads or a charger in the event of it running flat. This means that the converter can handle direct current voltages and convert them in both directions.

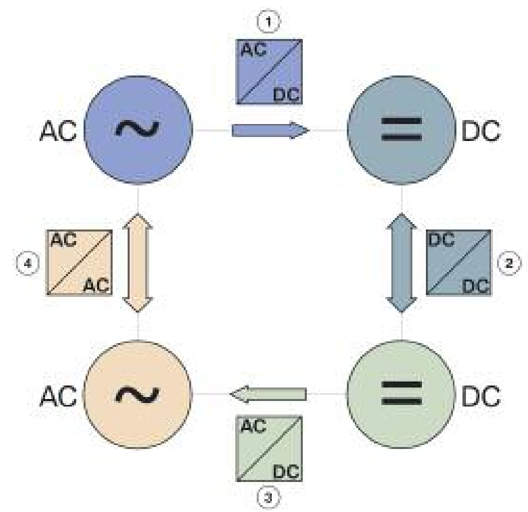
AC/AC Converter



Symbol used in circuit diagrams to represent an AC/AC converter

An AC/AC converter is used to convert an input AC voltage into an output AC voltage of a higher or lower level. It is also possible to convert alternating current voltages with transformers. But transformers are not included in the scope of power electronics. In other words, although an AC/AC converter does the same job as a transformer it does not consist of coils with an iron core; instead, it is designed as a circuit comprising power-electronics components.

Complete the legend for the following graphic



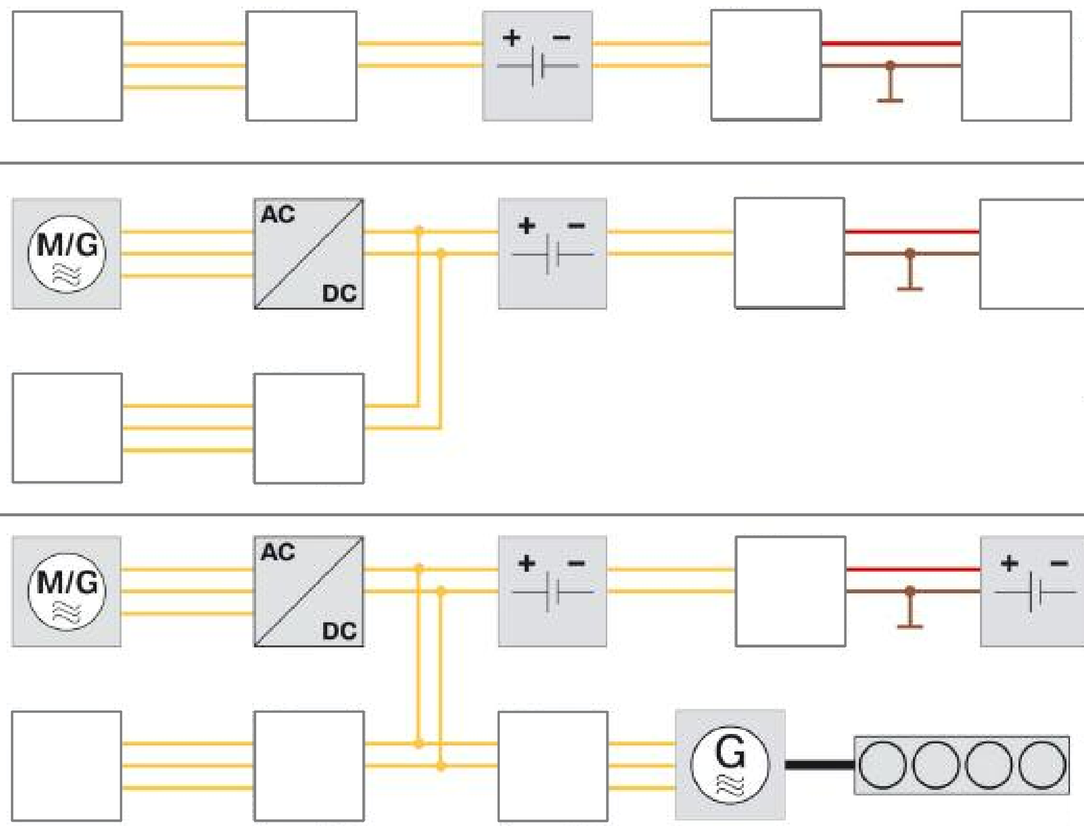
Index	Explanation	Index	Explanation
1		3	
2		4	

Complete the following graphic for different electrical powertrains.

Mild-hybrid

Full-hybrid

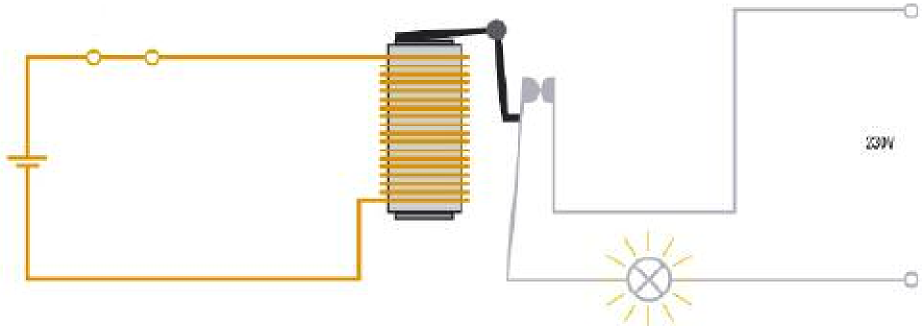
Serial Plug-in



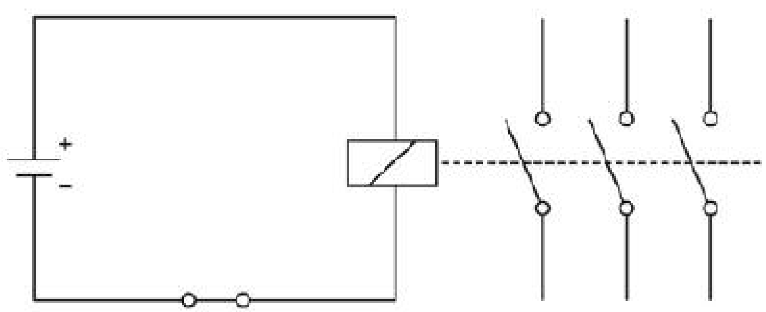
Electromechanical Switch Contactor

An electromechanical switch contactor is an electric switch for high-power switching actions. A switch contactor operates on much the same principle as a relay. The main difference is that a switch contactor can switch effectively at much higher power ratings than a relay; switch contactors operate in ranges from 500 watts up to several hundred kilowatts.

Operating principle of a relay

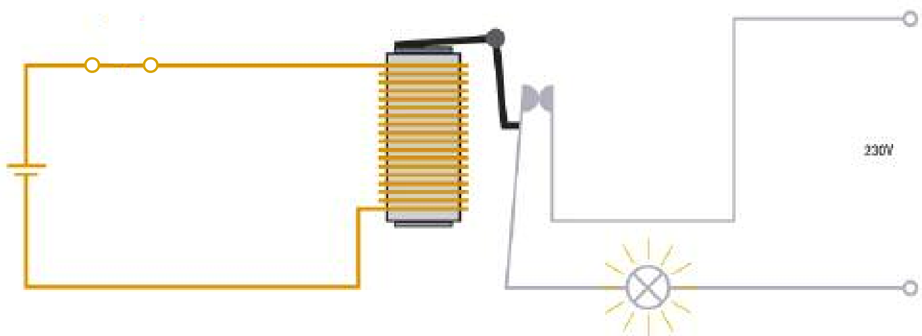


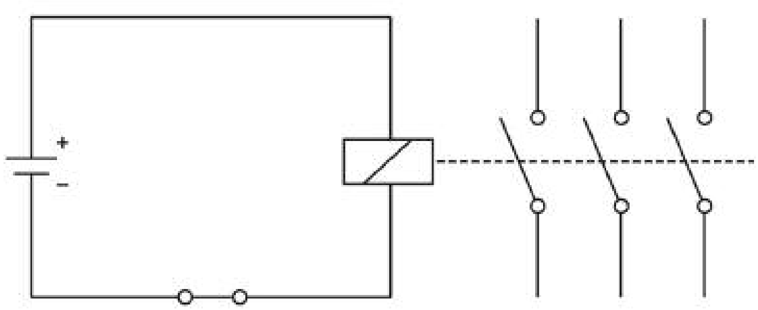
Symbol used in circuit diagrams to represent a switch contactor



The actuating coils of contactors can be designed for AC or DC voltage. On account of the high-speed tripping of the solid switch contacts, a switch contactor can be a source of mechanical vibration and noise when it throws. When a contactor switches off the actuating coil operating as an inductive load generates interference in the form of a voltage spike. An overvoltage protector has to be built into the circuitry to protect the control electronics. In alternating-current circuits a combination of resistor and capacitor (RC) is used for this purpose. A freewheeling diode can be used in DC circuits. RC combinations are also used to avoid breakaway sparking and electric arcs at the switch contacts.

In your on words, write down the difference between a relay and a contactor.





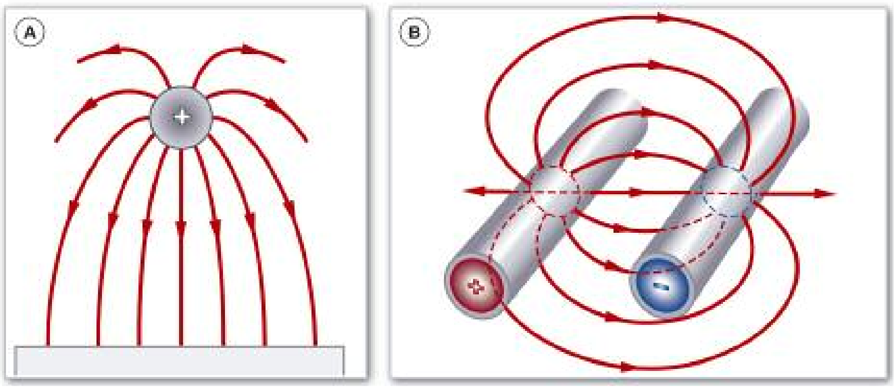
Safety

High Electric Voltage

Electrical Field

Every electrically charged object is surrounded by an electrical field. The effect is familiar and often experienced when a non-conductive object takes on an electrostatic charge. The electrical field is caused by the difference in potential between the electrically charged object and other objects in its vicinity. Instead of "difference in potential", we can also use the terms "electric voltage", or "electric tension".

Electrical fields of charged objects



Index	Explanation
A	Electrical field of a positively charged sphere
B	Electrical field of two electric conductors

Live electric conductors also generate an electrical field in their vicinity. The electric voltages encountered in the field of hybrid-auto engineering are in the order of magnitude of several hundred volts.

However, the field generated in this way does not constitute a direct hazard. The electrical field of an electrostatically charged object can be considerably stronger by comparison.

Electric Voltage as a Cause of Current Flow

As well as generating electrical fields in the vicinity of objects, electric voltage is also the reason why electric current flows in a circuit. The higher the voltage U the higher the current I for any given electrical resistance. In the high-voltage electrical system of a hybrid vehicle the voltages exceed those in the familiar 12-V systems by several orders of magnitude.

Example: given a fixed resistance of R = 1,000 Ω

at 12 Volts, the current would be 12 mA

at 120 Volts, the current would be 120 mA

at 360 Volts, the current would be 360 mA

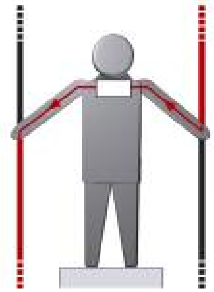
Needless to say, the technical components of the high-voltage electrical system are designed to have the resistances needed for the higher voltages involved, so the current flowing through the system is also of the desired level.

The resistance of the human body, however, is independent of the electrical voltage of any given external source to which it is exposed. Consequently, the current that would flow through the human body in the event of contact with live parts of a hybrid car's high-voltage electrical system would be much higher than in the case of a 12-V system.

The effect of electric current on the human body is discussed in this section.

Which hazards can be involved with electricity?

Electrical Shock



The cells in the human body are to a limited extent electrically conductive. The high proportion of liquid in the cells is one of the main reasons for this. If a person touches a live component, an electric current can flow through his or her body. The current invariably takes the shortest path through the body.

The organs affected by the electricity depends on the path taken by the current through the body. In the graphic above, the heart and the respiratory organs are among those affected.

Approximate resistances can be given for the various paths that current is likely to take through the human body. The human body's ohmic resistance to current can be dependant, but not limited to the following factors.

- Clothing
- Wetness of the skin
- Length of and nature of the path through the body.

The denser and drier the items of clothing at the parts of the body at which the electric current enters and exits the body, the higher the resistance. If the skin is wet from water or damp from perspiration, the body's electrical resistance is correspondingly lower.

If the current follows a short path through the body resistance is higher than if the current takes a longer route. The table below lists guideline values for the electrical resistance of the human body.

Path of Electrical Current (body)	Approximate Ohmic Resistance
From hand to 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

Electricity does not only have effects that can be used for technical purposes (heat, light, chemical and magnetic effects). Electricity is also capable of producing effects in living organisms, including the bodies of human beings.

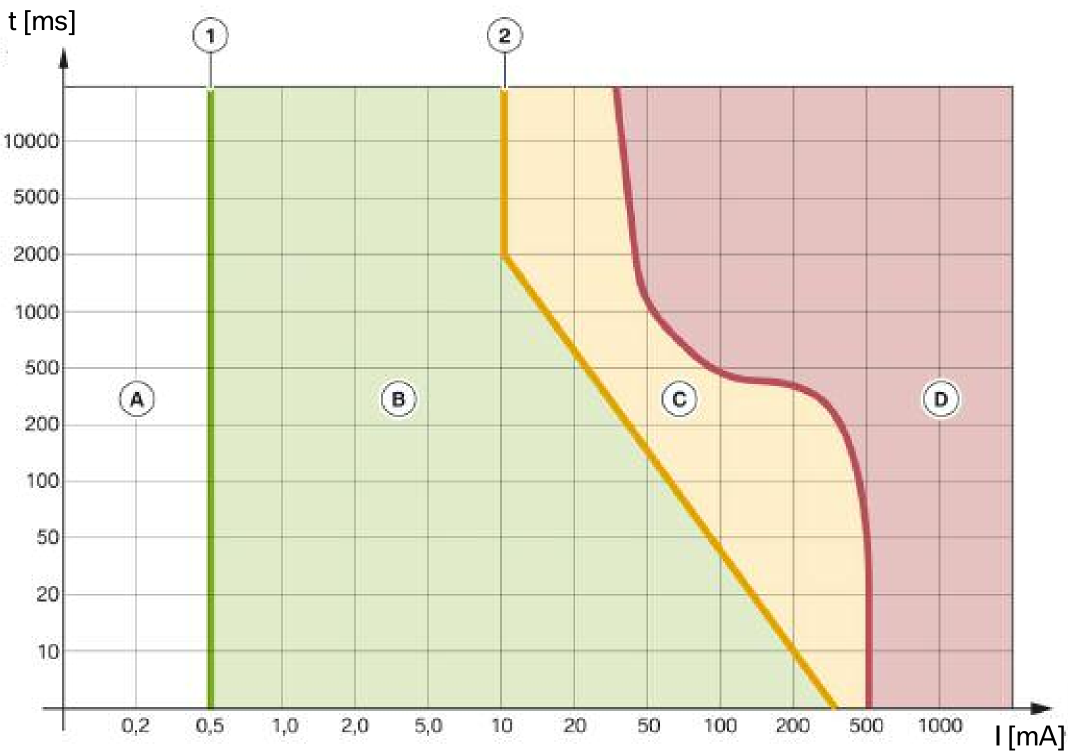
This is what is termed the physiological effect. The reason for this is that many functions of the human body are controlled by electrical processes. The movements of our muscles are produced by electrical impulses, and this also includes our heartbeat.

Similarly, the information provided by the sensory organs is carried by electrical means through the nervous system to the brain. And the human brain itself operates with electrical signals. These signals within the human body emit only minute voltages (mV) and currents (A).

If an electric current from an external voltage source flows through the human body, it overlays the body's natural electrical signals. This can have a massively disruptive effect on the natural electrical processes that take place all the time in the human body. The effect is usually perceived as an electric shock, and the natural response is to jerk back, away from the source.

If the current is strong the reactions of the muscles become uncontrollable. A muscular spasm can occur with the result that the live part is tightly clenched and cannot be released. This let-go limit is important, because once it is passed a very dangerous loop is closed: the longer the current is able to flow through the body the more damaging are its effects.

Time is money??? Not only money, but in terms of electricity…



Take notes about the areas and lines shown in the diagram:

A __________

B __________

C __________

D __________

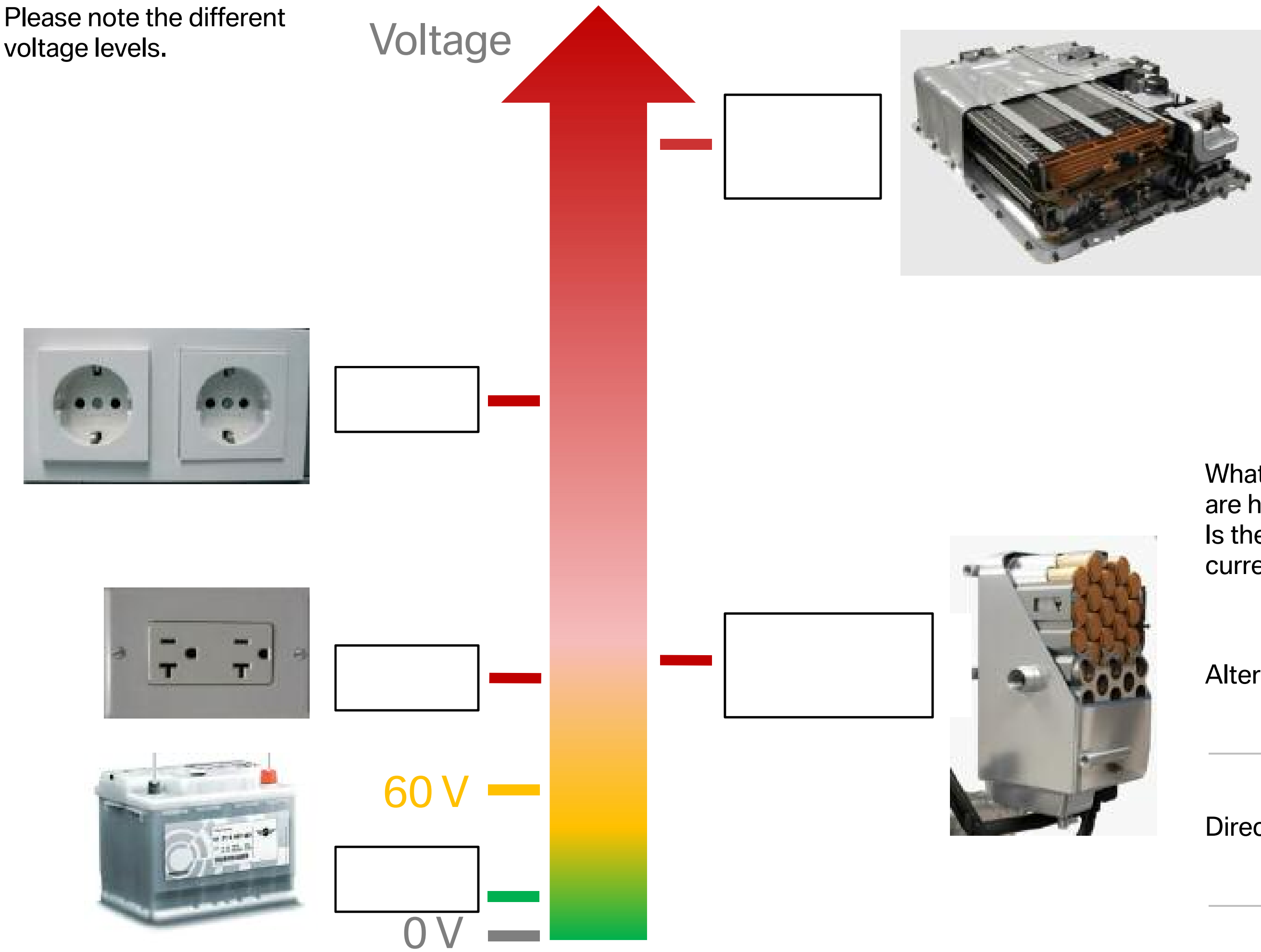
1 __________

2 __________

Principles of Hybrid Technology.

Safe working practices > Hazards involved with electricity > Voltage used in hybrid cars

Please note the different voltage levels.



What are the voltage limits, from which on they are hazardous (according to the ISO standard)? Is there a difference between alternating current (AC) and direct current (DC)?

Alternating Current (AC):

Direct Current (DC):

The most dangerous disruption of normal muscular activity affects the respiratory muscles and the cardiac muscle. This can cause apnoea, the cessation of movement of the respiratory muscles. Depending on current strength, the length of time during which current continues to flow, and the frequency (alternating current), ventricular fibrillation. This is a condition of feeble, high-frequency contractions of the heart muscle, which are insufficient to maintain the circulation of the blood.

Apnoea and ventricular fibrillation both cause a breakdown of blood circulation, which means that the supply of oxygen to the body's vital organs is cut off. These are conditions of acute danger to life.

Under these circumstances immediate first aid is absolutely essential to rescue the victim from injury or fatality.

Burns

The heat developed by the electric current can also cause injury to and in the human body. External burns can be suffered, primarily due to arcing. Internally, the electric current heats up the tissue through which it flows. The body fluids in particular can become hot enough for evaporation to occur.

Injuries of this nature are known as internal burns. The organs can cease to function within a very short time and the blood ceases to circulate. These are conditions of acute danger to life.

These are the immediate effects of severe electric shock, but there are also others that might only emerge some time after the actual incident. Even then it is possible for mortally dangerous situations to develop. For example, it takes some time for body cells destroyed by an incident involving exposure to electricity to be broken down by natural processes. In fact, the process can take several days.

The substances produced in this way have to be passed through the kidneys. If dead cells in very large numbers are present the kidneys can become overloaded and kidney failure can be the result.

Consequently, it is absolutely essential to ensure that after receiving first aid, the victim of an electric shock is thoroughly examined and re-examined by a professional physician.

Arc Flash

An arc flash occurs when current flows between two conductors across a gap containing a gas (e.g. air). This gap is usually of an insulating or poorly conductive nature.

An arc flash can occur when two conductors are initially brought into contact with each other and a current flows. Subsequent separation of the conductors initially produces only a very narrow gap between the two. Since the gap is narrow the electric field is extremely strong and might be higher than the breakdown strength of the gas occupying the gap.

Under these circumstances sparkover occurs and gas molecules are ionized. Ions and electrons are violently released from the material of the two conductors, and the result is that after the sparkover the material evinces signs of wear and tear. Another result is that charge carriers capable of migrating are produced: positively charged ions and negatively charged electrons. Because of the presence of the electrical voltage, these charge carriers migrate across the gap to the corresponding conductors. They then react with the conductors. When charge carriers move, their movement means that electric current flows. This mode of producing a current flux in gases is known as gas discharge. In the case of an arc flash this is a continuous process. New charge carriers are produced in succession and the current continues to flow. The gaseous matter between the conductors assumes the state in which it is known as plasma.

A light arc cannot flash between two conductors unless the voltage reaches a certain minimum level and the current flows at a certain minimum strength (before the conductors are separated). These values cannot be positively stated because they depend on the material of which the conductors consist.

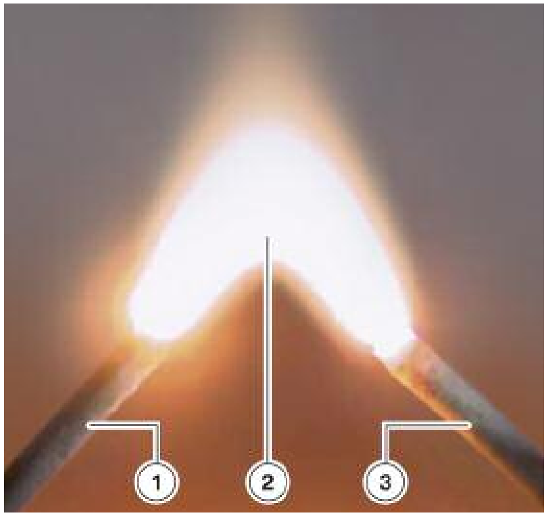
In the plasma between the two conductors the migrating charge carriers collide and cause the gas to heat up. Depending on the material of the conductors and the surrounding gas in the plasma, temperatures can reach approximately 4000°C or higher. These extremely high temperatures can release other charge carriers from the material of the conductors. This sustains the arc and causes steady attrition of the conductor material as it is "burned up".

This consumption of the material is an effect that has to be taken duly into account in terms of technical design: arcing that occurs at switch contacts as they open erodes the contacts. This is why the manufacturer generally guarantees the operation of relays or switch contactors for only a limited number of switching operations.

Electric arcs are also a source of danger to humans:

- Burns: the very high temperatures involved inevitably cause extremely severe burns if a person comes too close to an arc or penetrates directly into the arc. Keep well clear of electric arcs and use suitable protective gloves to hold the conductors.
- Ultraviolet radiation: the colliding charge carriers produce not only heat but also light with ultraviolet (UV) components. This UV light can cause injury to the eyes, and more specifically to the retina. This causes the painful condition known among welders as "eyeflash" or simply "flash", otherwise often referred to as "welding flash". Never look directly into an electric arc - always wear a protective facemask.
- Flying particles: ions and electrons are constantly shed from the conductors in the high-temperature zone produced by the electric arc. The process can also cause small particles of the material to break off in an uncontrolled manner. These tiny particles are often tremendously hot. Keep well clear of electric arcs unless you are wearing suitable protective clothing (including protective gloves and eye protection).

Electric arc between two conductors



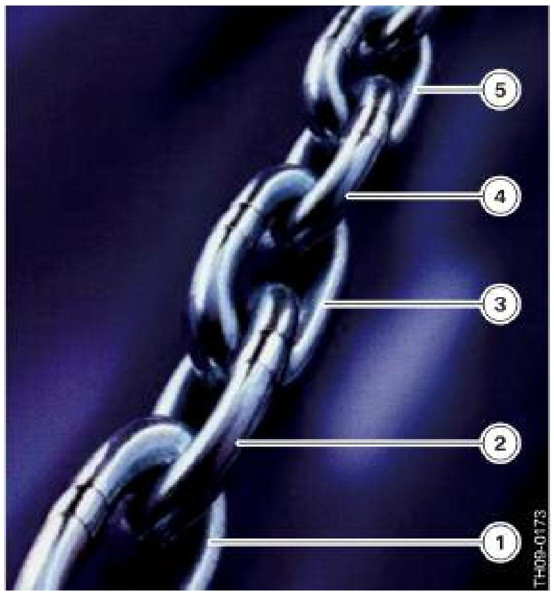
Index	Explanation
1	Conductor
2	Electric arc
3	Conductor

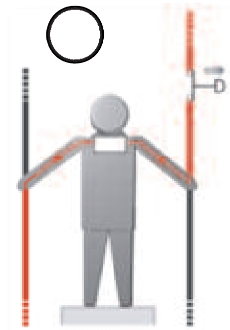
Principles of Hybrid Technology.

Safe working practices > First aid in case of electrical accidents

How do you help a person who had an electrical accident?

Build a survival chain and sort the actions to be taken into the correct sequence!

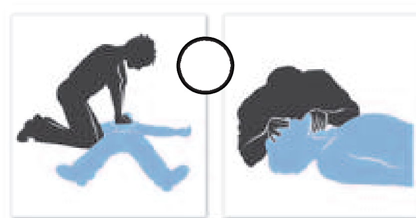




Interrupt the circuit

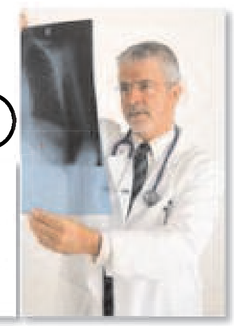
Think and secure

Send out emergency call



First aid

Help by emergency service



Post-accident medical treatment

Notes:

Preventing Hazards

Every individual working in the Service sector bears responsibility for the discharge of certain important duties with regard to health and safety at work:

- Always comply with verbal instructions and written rules concerning health and safety.
- Always make adequate use of the protective devices provided.
- Always use the facilities (tools, vehicles) in accordance with instructions.
- If equipment is found to be defective, make sure that it is correctly restored to full working order.

Each individual not qualified to undertake such repairs themselves must immediately notify their superior to have the repairs duly undertaken at the earliest possible opportunity.

The ISO community has deemed the following voltage levels to be hazardous:

- Alternating current (AC) voltages of 25 V or higher
- Direct current (DC) voltages of 60 V or higher

A voltage is defined as being hazardous on the basis of the consequences resulting when a person touches a live part. The voltage is defined as "hazardous" when the current flowing through the person's body can cause injury to health. In hybrid cars the components that work at hazardous voltages are referred to collectively as "high-voltage components".

High-voltage components are identified either by the warning label shown below or by a high-visibility orange color (as is the case with high-voltage cables).

Example of a high-voltage warning label

The principle health and safety rule is simple:
Never work on live components!

Consequently, before starting work it is essential to de-energize the system in question and make sure that it cannot be re-energized without the knowledge and consent of the person undertaking the work.

Other, specific, more detailed health and safety rules are derived from this principal rule. Each and every individual involved in Service must always apply these rules before starting and while working on high-voltage components. Strict compliance with these rules is absolutely essential in order to ensure health and safety.

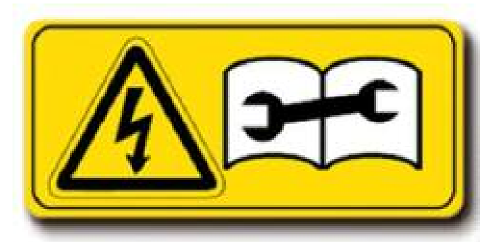
The three safety rules for hybrid vehicles are as follow:

1. De-energize the system
2. Secure the system so that it cannot be re-energized without your knowledge and consent
3. Check that the system is de-energized

Principles of Hybrid Technology.

Safe working practices > Safety rules to prevent electrical hazards > Identify high voltage components

How can high-voltage components be identified?

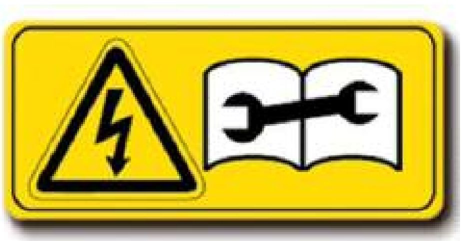


When working on the BMW ActiveHybrid vehicles in the service center, the high-voltage system will be entirely de-energized.

Under absolutely NO condition may a high-voltage system or component be worked on with the high-voltage enabled.

Work on any vehicle's high-voltage system may only be performed by a certified and trained service technician.

The three safety rules MUST always be adhered to when working on a vehicle's high-voltage system.



Do not work on LIVE high voltage parts!

Please write down the three safety rules for working on high voltage components in the correct order.

1 ______________________________

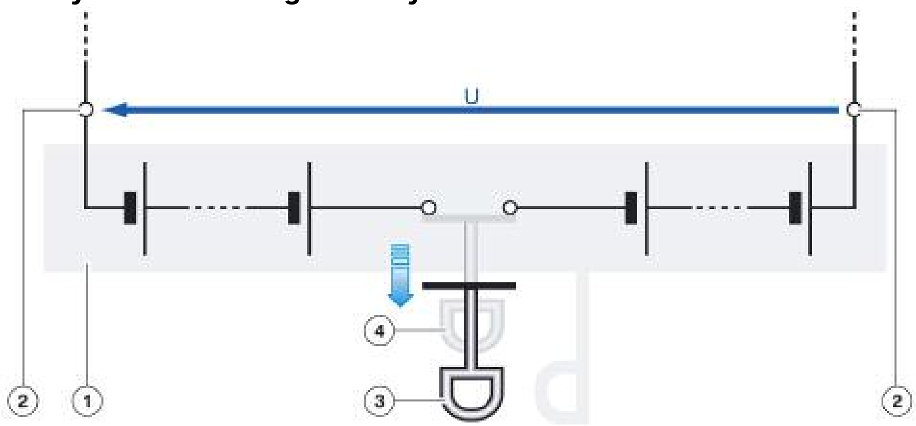
2 ______________________________

3 ______________________________

Safety Rule 1 - De-energize the System

A service employee working on high-voltage components can come into contact with components such as the connections of the high-voltage cables. While the vehicle is in operation these live components carry hazardous voltages. Service employees must be able to work under conditions that do not entail risk to health and safety, so when work is to be undertaken all the high-voltage components must be "dead", in other words free of hazardous voltage. The simplest possible way of achieving this is to remove the energy source, in other words the high-voltage battery, by disconnecting it from the circuit. This can be accomplished as shown in the graphic below.

Safety rule 1: de-energize the system



Index	Explanation
1	Housing of the high-voltage battery
2	External connections of the high-voltage battery
3	High-voltage safety switch pulled (disconnected)
4	High-voltage safety switch inserted (system is live)

This effectively pulls the plug on the series-connected battery cells. Once the voltage source has been disconnected in this way, the externally accessible poles of the high-voltage battery are no longer live.

The connector, the plug at which the connection is broken, is called the "high-voltage safety switch" but in technical jargon it is also frequently referred to as the "Service Disconnect".

In the vehicles, the current range of the high-voltage safety switch varies in appearance and configuration from model to model. By way of example, the illustration above shows the type used in the BMW ActiveHybrid X6.

High-voltage safety switch for the BMW ActiveHybrid X6

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

As an alternative to disconnection of the series-connected battery cells, there is another way in which the high-voltage safety switch can be used. In this respect, the high-voltage safety switch acts as control input for a control unit. The control unit immediately interrupts the supply to the switch contactors, as soon as it establishes that the high-voltage safety switch has been pulled. The contacts of the switch contactors respond by opening automatically.

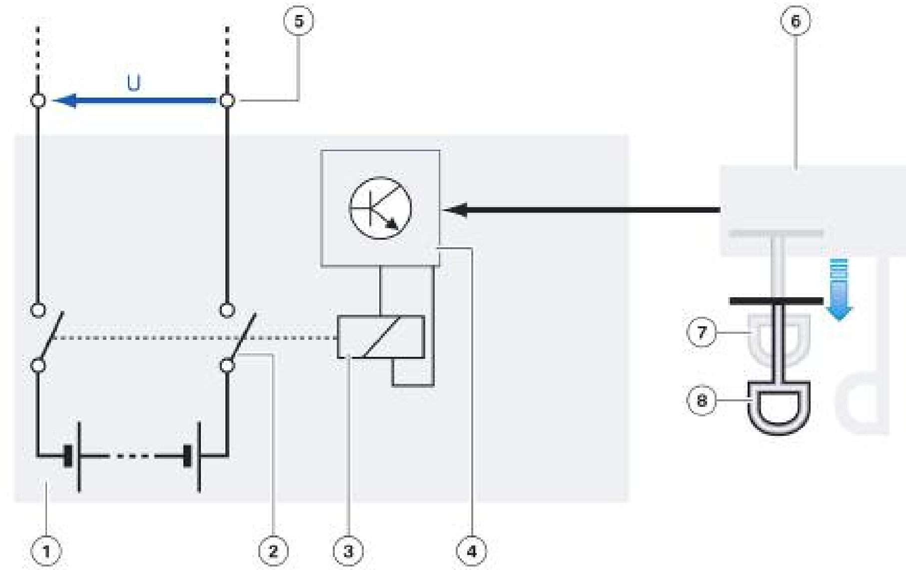
The effect is the same as disconnection of the series-connected battery cells: once the high-voltage safety switch has been pulled there is no longer a hazardous voltage present at the external poles of the high-voltage battery.

When the high-voltage safety switch is pulled, several processes take place automatically and in parallel in the high-voltage system. This ensures that hazardous voltage is no longer present at the poles of the high-voltage battery, at electronic components, or at the electrical machine or machines:

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.

These measures, once implemented, avert the major hazards that could otherwise threaten Service employees. But what would happen if someone else (intentionally or unintentionally) reinserts the high-voltage safety switch? If this were to happen there would be a possibility of a hazardous voltage being applied to components being worked on or about to be worked on, and this would of course constitute a major hazard to health and safety. Consequently, not only does the high-voltage system have to be de-energized, it also has to be secured so that it cannot be re-energized without the knowledge and consent of the person undertaking the work.

Safety rule 1: de-energize the system (via monitored safety circuit)

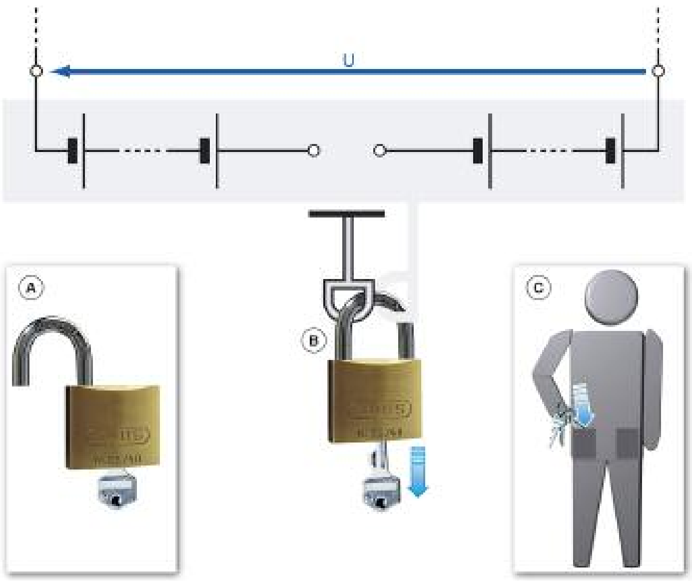


Index	Explanation
1	Housing of the high-voltage battery
2	Two switch contactor contacts
3	Switch contactor solenoid
4	Control unit that evaluates the state (pulled/inserted) of the high-voltage safety switch and actuates the switch contactor accordingly
5	High-voltage connections of the high-voltage battery
6	Separate housing for the high-voltage safety switch
7	High-voltage safety switch inserted (system is live)
8	High-voltage safety switch pulled (disconnected)

Safety Rule 2 - Secure the System (Lockout)

Once the high-voltage safety switch has been pulled, the high-voltage system can be secured at the switch to ensure that it not switched on again. This entails installing a conventional padlock. Once the high-voltage safety switch has been pulled and secured in this way, it cannot be reinserted until the padlock has been removed. The person working on the high-voltage system has the key of the padlock in safekeeping until all work on the high-voltage system is completed.

Safety rule 2: Secure the system so that it cannot be re-energized without your knowledge and consent



Index	Explanation
A	Use an open padlock
B	Secure the high-voltage safety switch in its pulled position by engaging the padlock
C	Keep the key of the padlock in a safe place at all times

This simple precaution suffices to ensure that no-one else can switch on the high-voltage safety system until all work on the system has been completed. This rules out inadvertent endangerment of the persons working on the high-voltage system not only before work commences, but also for as long as it takes to complete all the work in question.

Safety Rule 3 - Ensure that the system is de-energized

Once the person who is going to work on the high-voltage system has de-energized the system and locked the switch so that it cannot be switched on again without the key, there are still certain safety rules that have to be applied.

The next step is a check to ensure that the high-voltage system is in fact de-energized and safe. In BMW vehicles, it is not necessary to use an external tester for this step in the procedure. The design of the high-voltage system is such that the system itself can tell that it has been de-energized. Several high-voltage components measure their own voltage, using integrated circuits for voltage measurement.

The results of these measurements are transmitted via bus systems to the instrument panel. When the results of all these measurements show a voltage that is below the hazard threshold, the instrument panel shows a symbol indicating that the high-voltage system has been successfully powered down and is no longer live.

In this Check Control symbol, the danger symbol representing high-voltages (lighting flash) is struck through. The symbol is therefore a visual indicator clearly emphasizing that there is no longer a hazardous voltage present in the system. Depending on the vehicle type, the symbol actually shown in the instrument panel might not necessarily be exactly as illustrated here. Consult the instructions in the repair manual or the training media for the vehicle type in question to ascertain precisely which symbol is used to indicate this state.

This is the third safety rule and once again it is essential to apply it before starting work on high-voltage components. The procedure is a simple a check to ensure that the high-voltage system has been correctly switched off and has safely de-energized. The check ensures that the high-voltage system is not a source of danger for persons working on the vehicle.

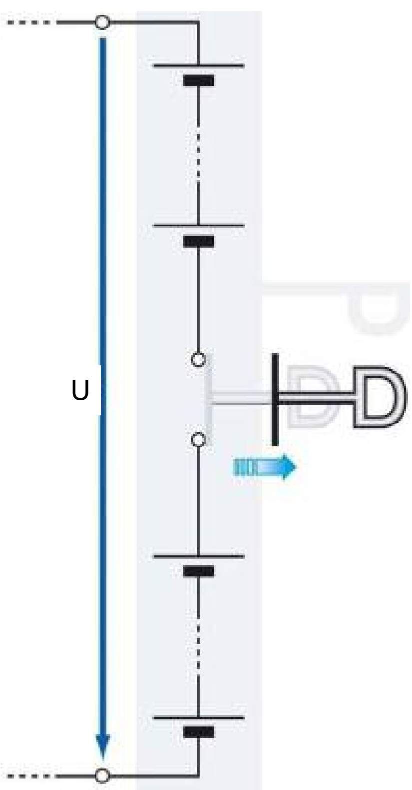
Check Control symbol: high-voltage system is de-energized and safe

Note: No external measuring equipment will be necessary. Various engineered safety measures have been implemented on the BMW ActiveHybrid vehicles that ensure safety.

Under NO condition should work on a high-voltage component be carried out if this check control message does not appear. The high-voltage system will be considered energized. A PuMA case MUST be submitted.

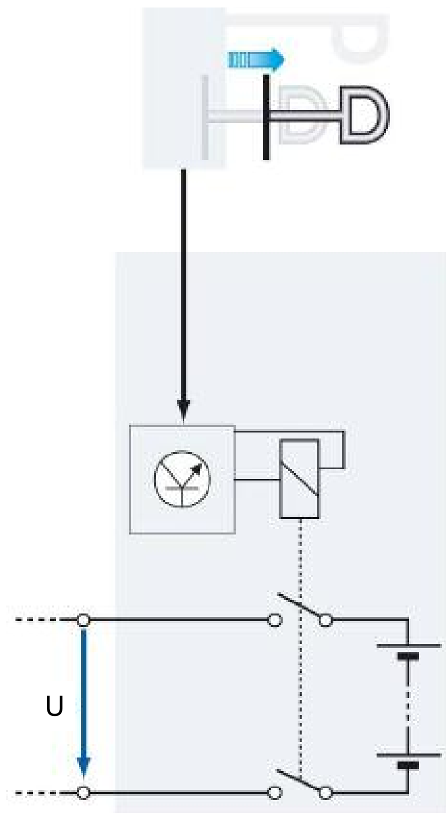
Principles of Hybrid Technology.

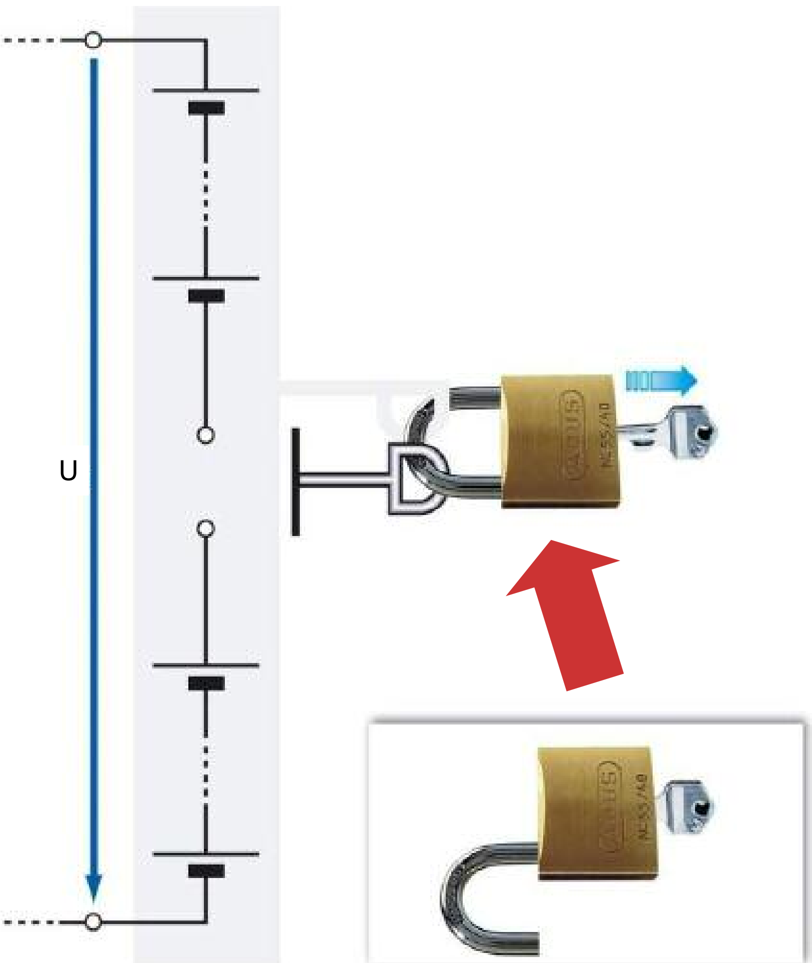
Safe working practices > Safety rules to prevent electrical hazards > First step: de-energize the high voltage system



Use the high voltage safety connector ("service disconnect") to de-energize the high voltage system!

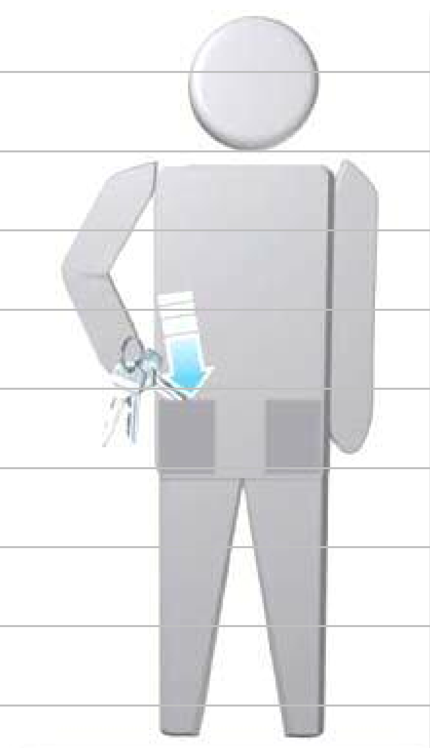
There are two different ways, how the high voltage safety connector works. Note similarities and differences.





Use a pad lock to secure the high voltage system, so that it cannot be re-energized without your consent!

Where will you put the key, while you are working on the high-voltage system?



Principles of Hybrid Technology.

Safe working practices > Safety rules to prevent electrical hazards > Third step: Check that the high voltage system is de-energized

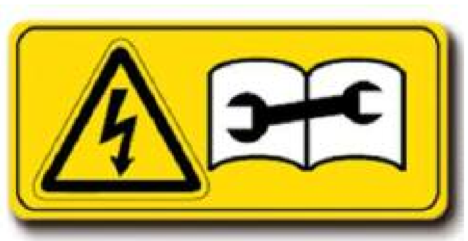
Check, that the high voltage system is de-energized!

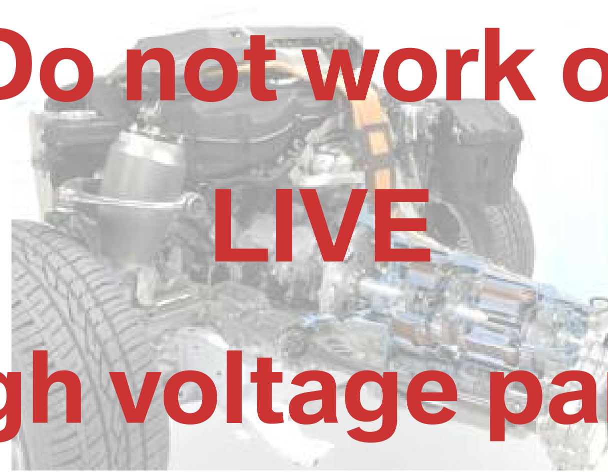
Will you need any special tools? Do you have to use the IMIB?

Can you check it at the instrument cluster? Why/why not?

BMW E72 KOMBI

BMW F04 KOMBI





Do not work on LIVE high voltage parts!

Please write down the three safety rules for working on high voltage components in the correct order.

1 ______________________________

2 ______________________________

3 ______________________________

Nickel Metal Hydride Battery
Nickel metal hydride (NiMH) batteries, if used correctly and kept free of damage, are not a direct source of endangerment. The casing is designed to ensure that fluids (electrolyte, for example) cannot escape at any point in the entire usable lifespan of the battery. If the casing is damaged, as can happen for example in the event of an accident or if the battery is not used correctly in accordance with the manufacturer's instructions, NiMH batteries can be a source of endangerment as follows:

- Chemical burns (electrolyte)
- Injury to health (electrolyte, coolant)
- Fire/explosion.

A solution of potassium hydroxide is used as the electrolyte in NiMH batteries. This solution is classified as a caustic irritant. In the event of electrolyte escaping from a NiMH battery, it is important not to come into contact with the spilled liquid. Obtain medical assistance if a person is wetted by or swallows the electrolyte. Notify the fire service in the event of a spillage: the fire service has the special equipment needed to deal correctly with the spilled electrolyte.

Comply with the instructions set down in the safety data sheet on how to proceed in the event of electrolyte escaping from a nickel metal hydride battery.

NiMH batteries can develop full power only within a limited ambient temperature range. Consequently, the battery is connected to an on-board cooling circuit. The coolant is the same as that commonly used in BMW vehicles. It is hazardous to health and under no circumstances should it be swallowed or allowed to come into contact with the skin.

When NiMH batteries are charging or discharging, the chemical reactions involved produce gases (oxygen and hydrogen, respectively). These gases can escape through a breathe valve in the casing of the nickel metal hydride battery. When the battery is used correctly in accordance with the manufacturer's instructions the concentration is low and poses no hazard (according to information provided by manufacturer).

In order to diminish the possibility of explosion, always keep fire, sparks and all other sources of ignition well away from NiMH batteries.

NiMH batteries bear labels showing hazard symbols to indicate the possible dangers.

Principles of Hybrid Technology.

Safe working practices > Hazards involved with electricity > Chemical dangers

Write down the meanings of the symbols on the label of a nickel metal hydride battery:

1 ______________________

2 ______________________

3 ______________________

4 ______________________

5 ______________________

6 ______________________

7 ______________________

8 ______________________

Lithium-ion Battery
Similarly, the Lithium-ion batteries in BMW vehicles are safe when used correctly in accordance with the manufacturer's instructions and kept free of damage. It is important to note, however, that restrictive conditions apply to correct usage. In particular it is very important to ensure that Lithium-ion batteries are not overcharged and not exposed to excessively high temperatures.

Overcharging can cause metallic lithium to deposit on the positive electrode and destroy the negative electrode. If this is allowed to happen the temperatures at the battery rise and the Lithium-ion battery can catch fire. In BMW vehicles the control unit of the Lithium-ion battery ensures that charging and discharging cycles take place only within the specified boundary conditions. Sensors are used to monitor cell temperature and cell voltage. The control unit intervenes in the charging or discharging process as necessary. This applies both when the vehicle is in use and in circumstances in which the high-voltage battery is charged off a charger connected to the 12-V system.

Do not expose Lithium-ion batteries to excessively high temperatures. Operating temperatures higher than approx. 50°C suffice to accelerate the aging process and shorten battery life. If the cells are permitted to reach temperatures of 100°C or higher a short-circuit can occur between the cells. The high currents that flow if the cells short further increase temperature and a chain reaction can occur. The entire Lithium-ion battery would suffer irreversible damage and could catch fire.

It is difficult to extinguish a Lithium-ion battery if it catches fire. However, there is no direct risk of the battery itself exploding. Nevertheless, the high temperatures produced by the fire could ignite objects, liquids or gases in proximity to the battery and this in turn could cause an explosion.

The upper limit for operating temperature is very firmly defined, so Lithium-ion batteries in BMW ActiveHybrid vehicles are cooled. For example, they can be connected directly to the refrigerant circuit of the air conditioning system. Consequently, it is essential to comply with the repair instructions and the instructions in the applicable safety data sheets for all work on Lithium-ion batteries and in particular when opening the connections to the refrigerant circuit.

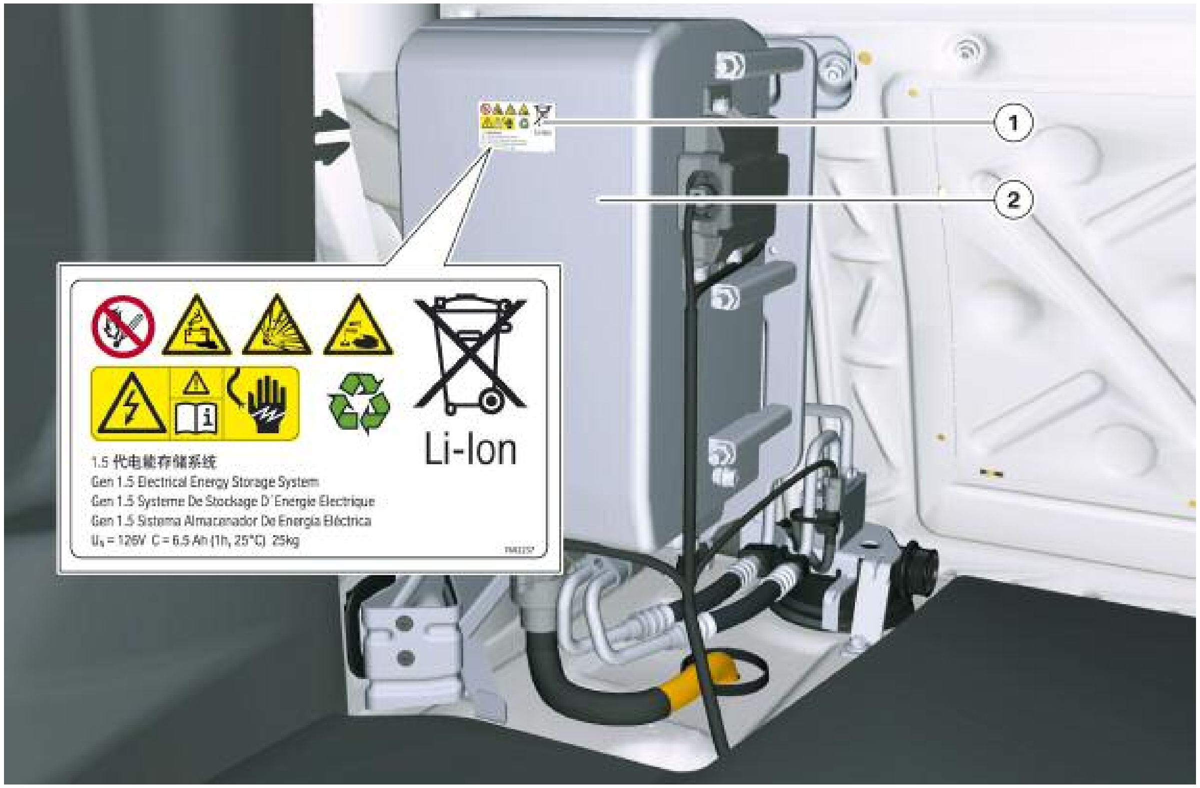
Strict compliance with the repair instructions for work on the refrigerant circuit – and this includes Lithium-ion batteries – is essential in order to preclude the possibility of a health hazard.

The Lithium-ion batteries used in BMW vehicles have hermetically sealed casings. The only external connections are the high-voltage terminals and the coolant lines. Even so, special precautions also apply to using and working with high-voltage batteries of this kind.

Note: Never attempt to open the casing of Lithium-ion batteries. Never attempt to operate or charge a battery of this kind unless it is connected to the appropriate control unit. Failure to comply with these precautions will result in a risk of fire

Note: It is recommended that only a specially trained person attempt to extinguish a fire caused by a Lithium-ion battery.

Lithium-ion battery (F04)



Index	Explanation
1	Warning label
2	Casing

What are some reasons that a Lithium-ion battery can catch fire?

What affect will one galvanic cell that catches fire have on a Lithium-ion battery?

Electrical Machines

High output is a characteristic of the electric drive in every BMW ActiveHybrid, so the electrical machines operate with very strong magnetic fields. These fields are generated by permanent magnets or electromagnets. It is important to bear in mind that the magnetic fields of permanent magnets are also permanent, in other words they are present even if the high-voltage system is switched off or the electrical machine has been removed.

These magnetic fields can interfere with electronic medical devices, particularly cardiac pacemakers.

The components in question bear a prohibition label drawing attention to this specific hazard. By way of example, the illustration to the right shows this label affixed to an electrical machine.

Persons who need a cardiac pacemaker or other electronic medical device to maintain their health are not permitted to work on components bearing the prohibition label shown here.

Prohibition: People with cardiac pacemakers should not approach

Classroom Exercise - Review Questions

1. What steps must be followed if a person is found on the floor and electric shock is suspected?

2. What type of high-voltage battery is the BMW ActiveHybrid X6 equipped with?

3. When working on a high-voltage component, what three safety rules MUST be followed? And why?

4. What is the proper course of action if the high-voltage de-energized check control message does not appear on the KOMBI?

Engineered Safety Measures

The BMW ActiveHybrid vehicles in general and the high-voltage components in particular are designed and built to be inherently safe. This means that faults that could lead to endangerment of the vehicle user are reliably detected and identified. Such detection and identification leads to immediate shutdown of the high-voltage system, with the result that there are no longer hazardous voltages present at active components of the system. Shutdown is initiated automatically for example if a cover of a high-voltage component is removed.

The high-voltage system is also of fault-tolerant design in order to ensure that the vehicle user does not have to stop on account of every minor fault. This means that the occurrence of a single fault does not cause direct endangerment. Self-diagnosis of the high-voltage components ascertains the presence of these faults, however, and logs them in fault memory.

Nonetheless, the vehicle can proceed on its way without any risk.

The list below provides an overview of the engineered-safety measures that are used in the high-voltage system of BMW ActiveHybrid vehicles.

- Identification labelling
- Guarding to prevent accidental contact
- High-voltage interlock loop
- Discharge of the high-voltage circuit
- Galvanic separation of the high-voltage electrical system from the 12 V electrical system
- Short-circuit monitoring
- Shutdown in the event of an accident

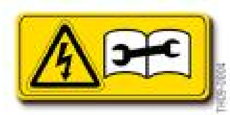
Identification/labelling of High-voltage Components

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.

The warning labels are all based on the internationally standardized and universally familiar warning signs for hazardous electrical voltage. On this basis, two different warning signs are currently used in BMW ActiveHybrid vehicles to identify high-voltage components.

Both these labels contain an extra symbol prompting the service employee to consult the appropriate repair information. The document in question contains the information relevant to correct procedures for safety in handling and working with the high-voltage component in question. The labels of the second type also contain a third symbol drawing attention to the possibility of an electric shock hazard.

Warning: hazardous electrical voltage



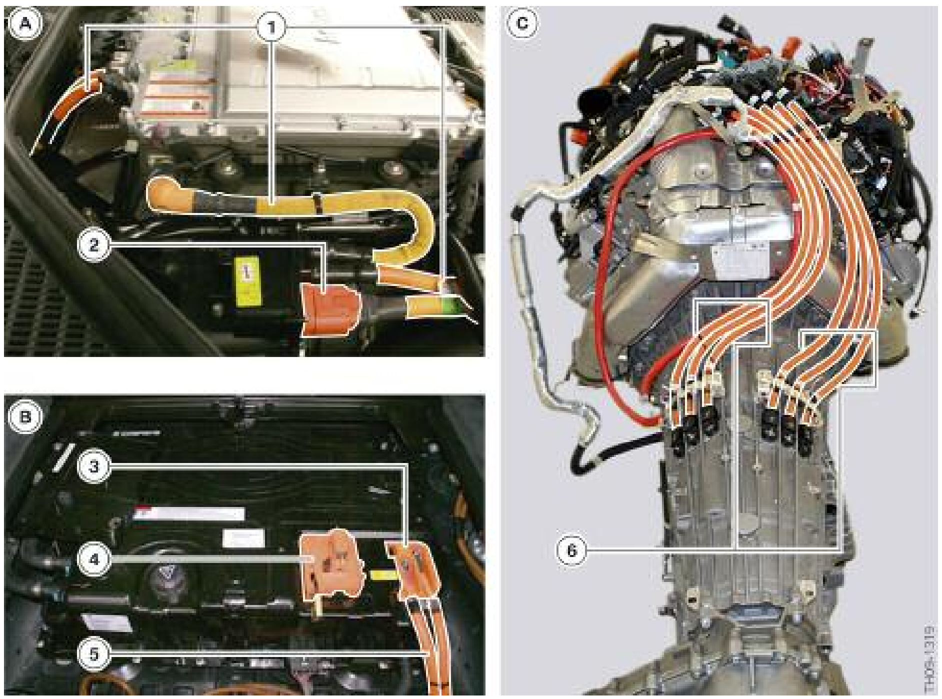
Warning for high-voltage component, type 1

Warning for high-voltage component, type 2

The means of identifying high-voltage cables is a special instance. These cables can be several meters in length, so there would be little point in relying on one or two labels affixed at arbitrary points sufficing under all imaginable circumstances to identify a cable as carrying high-voltage. Labels of this nature would be easily overlooked. Instead, all high-voltage cables have bright orange sheaths. Some connectors for high-voltage cables and the high-voltage safety switch can also be bright orange.

The manufacturers of hybrid vehicles have agreed on a unified system of identification for the high-voltage components based on the warning labels shown above and the use of orange as a warning color for high-voltage cable.

Orange coloring of the outer sheath identifies the high-voltage cables



Index	Explanation
A	Orange coloring identifying cables and components in the engine compartment
B	Orange coloring identifying components at the high-voltage battery
C	Orange coloring identifying components at the active gearbox
1	High-voltage cables in the engine compartment
2	Connector on a high-voltage cable
3	Terminals on the high-voltage battery
4	High-voltage safety switch (Service Disconnect)
5	High-voltage cables at the high-voltage battery
6	High-voltage cables at the active gearbox

Protection Against Direct Contact

Guarding to prevent accidental contact is a term that covers a number of basic technical measures for electrical systems that are adopted to ensure that no-one can inadvertently touch a live component carrying a hazardous voltage. There are two levels, namely basic protection (against direct contact) and fault protection (against indirect contact).

Basic protection describes the level of protection under normal operating conditions, in other words in the absence of faults. The housings and covers of the high-voltage system are shaped and assembled such that it is not possible to insert a finger in such a way as to come into contact with a component carrying a hazardous voltage.

There is an even higher classification of protection required at certain other locations in the vehicle. The next level of protection states that the enclosure is such as not to permit contact to be made with a component carrying a hazardous voltage even by insertion of a wire.

Basic protection also includes the insulation of active parts (live parts in other words) that can be inside or outside enclosures.

Protection Against Indirect Contact

The second level, fault protection, comprises additional protective measures over and above basic protection that prevent endangerment for humans even in the event of an electrical fault occurring. They include:

- Insulation of the high-voltage cables
- Network form of the high-voltage electrical system.

The high-voltage cables invariably have an insulating plastic covering. Outside this covering there is only a shield (wire braid/film) that is used for two purposes: to reduce electromagnetic interference and primarily for the purposes of insulation monitoring (see below). The shield is protected against mechanical damage (e.g. chafing) by a bright orange plastic outer sheath. The high-voltage cables are required to meet ultra-high requirements in terms of insulation resistance. Insulation resistance ratings in the order of magnitude of several megaohms is a must, and compliance is verified in post-production testing and monitored when the cables are in use. The implementation of these measures means that the high-voltage cables comply with the class II requirements for protection against direct contact.

Isolation Monitoring

The voltage source is not connected to earth (in automotive applications: to vehicle ground), no shortcircuit current flows. Consequently, a fuse would not be tripped in this situation. This in turn means that if a fault of this nature occurs, the high-voltage system can initially remain in operation. This ensures the high availability of the high-voltage electrical system and this constitutes a significant advantage of this network form. IT networks can be used not only for three-phase systems but also for the direct-current configurations that are also used for the high-voltage systems of hybrid vehicles.

If a person touches the enclosure (housing of the high-voltage battery) current does not flow through his or her body because the circuit to the voltage source is not closed. In fact, the circuit is not closed even if the person simultaneously contacts vehicle ground by touching the bodywork of the vehicle with some other part of the body. The only situation in which current could flow through the person's body would be if he or she were also to simultaneously touch a second live cable of the high-voltage electrical system. This clearly illustrates a second advantage of IT networks.

But how can a fault of this kind be detected and, ultimately, how can it be rectified? This is the reason why isolation monitoring is implemented in the high-voltage electrical system. Its purpose is to detect hazardous isolation faults between any live high-voltage component and electrically conductive enclosures or housing or between a component and ground. A hazardous isolation fault is present when a hazardous voltage is applied between housing/ground and another live high-voltage component. Or expressed in other terms, when the isolation resistance between a high-voltage component and housing/ground drops below a defined threshold.

The isolation monitoring circuitry in the high-voltage electrical system measures the system's isolation resistance, for example indirectly by a series of voltage measurements. Voltage is measured at precision resistors between live components (e.g. positive and negative poles of the high-voltage battery) and vehicle ground. These measurements take place both while the high-voltage system is live and after the high-voltage system has been switched off. Isolation monitoring is generally integrated into one or two high-voltage components, for example the power electronics and/or the control unit of the high-voltage battery. But how can isolation monitoring detect an isolation fault in another high-voltage component, such as the electric A/C compressor, for example?

Isolation monitoring at one or two central points 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 galvanic connection has to be present in order for example for the monitor implemented in the power electronics to reliably detect a short circuit in a high-voltage cable of the electric A/C compressor. In the absence of this galvanic connection between housing and ground the fault would remain undetected and would therefore constitute a potential hazard. The galvanic interconnection between the housings the connections from housing to ground is referred to as "equipotential bonding". The electrical connections established for this purpose are known as "equipotential bonding conductors" or simply "bonding conductors".

The electrically conductive housings of high-voltage components must be galvanically connected to ground. As regards repairs to high-voltage components, but also when body components are replaced, this has to be taken duly into consideration during assembly: it is essential to make sure that the galvanic connection between the housing and the body is correctly restored. In this respect too, it is very important to proceed precisely in accordance with the repair instructions. This applies most particularly to the use of the specified connecting elements (e.g. self-tapping screws) and compliance with the specifications for tightening torques.

High-voltage Interlock Loop

The live parts of the high-voltage components are protected against direct touch contact by covers or housings. Much the same applies to the conductors of the high-voltage cables: they are protected against touch contact by their insulating sheaths or by insulating connector housings. Before working on a high-voltage component, you must apply the safety rules to shut down the high-voltage system.

Once this has been accomplished according to procedure, the parts are no longer live and work can proceed in safety. There is of course a remote possibility that the correct shutdown procedure might be omitted, so an extra safety precaution is implemented as a means of imposing an automatic shutdown of the high-voltage system.

Covers over touchable live parts and plugs that have touchable contacts are integrated into the high-voltage contact monitoring circuit known as the high-voltage interlock loop. The principle of the high-voltage interlock loop is illustrated and explained below.

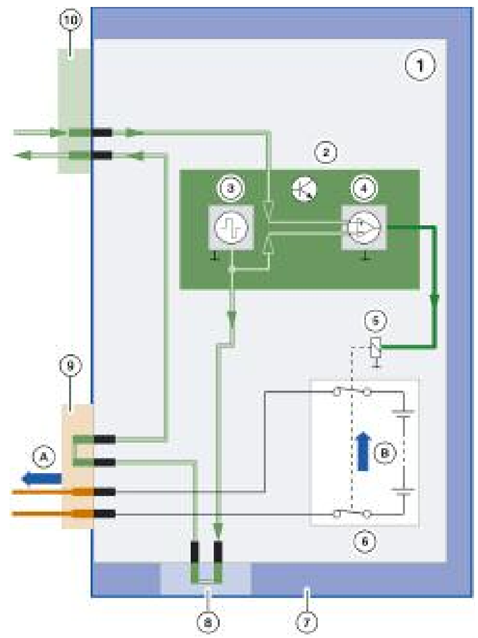
The electronics of the high-voltage interlock loop discharge two primary functions. The first is to generate the interlock signal. This is an alternating voltage (or an alternating current) that is generally a square wave with low values and therefore safe. The interlock signal is tapped into a circuit that runs over the covers of the high-voltage components and/or the connectors of the high-voltage cables.

There is a jumper in each cover or connector. When the cover is installed and secured, the jumper closes in the circuit of the high-voltage interlock loop. If the cover is removed and the jumper pulled, the circuit is interrupted. Much the same applies with the high-voltage connectors: if the high-voltage connector is inserted and locked the jumper closes in the circuit of the high-voltage interlock loop. If the connector is pulled, the jumper interrupts the circuit. The contacts of the high-voltage cables are recessed in the connectors. This means that when the connector is pulled the circuit of the high-voltage interlock loop is interrupted first, before the connection of the high-voltage cables is interrupted.

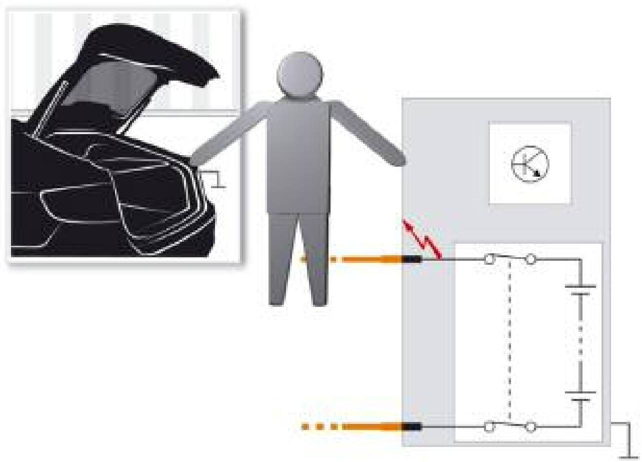
This enhances touch-contact protection and reduces the risk of an arc flashing across the contacts when the connection is broken.

The jumpers are connected in series in the entire circuit of the high-voltage interlock loop. Consequently, removing a single cover or pulling a single connector suffices to interrupt the interlock signal.

Result of opening the HVIL circuit

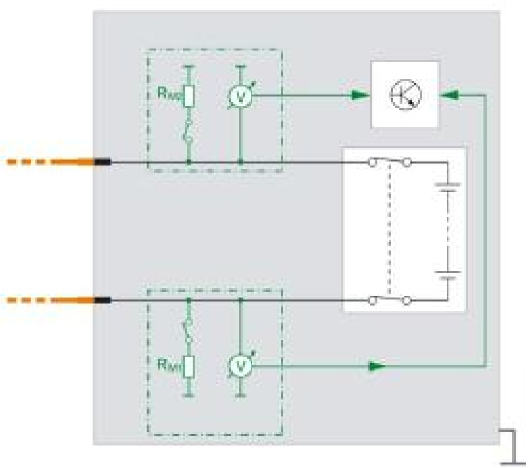


Index	Explanation
1	High-voltage battery unit
2	HVIL electronics
3	Signal generator
4	Evaluation circuit
5	Switch contactors
6	High-voltage battery
7	High-voltage safety cover
8	Jumper - HV safety cover
9	Jumper - HV connector
10	12V connector
A	Removing HV connector
B	Switch contactors open



What happens if

- an insulation failure at the high voltage system occurs
- and a human touches the housing of the corresponding component?



How does the insulation monitoring work in principle?

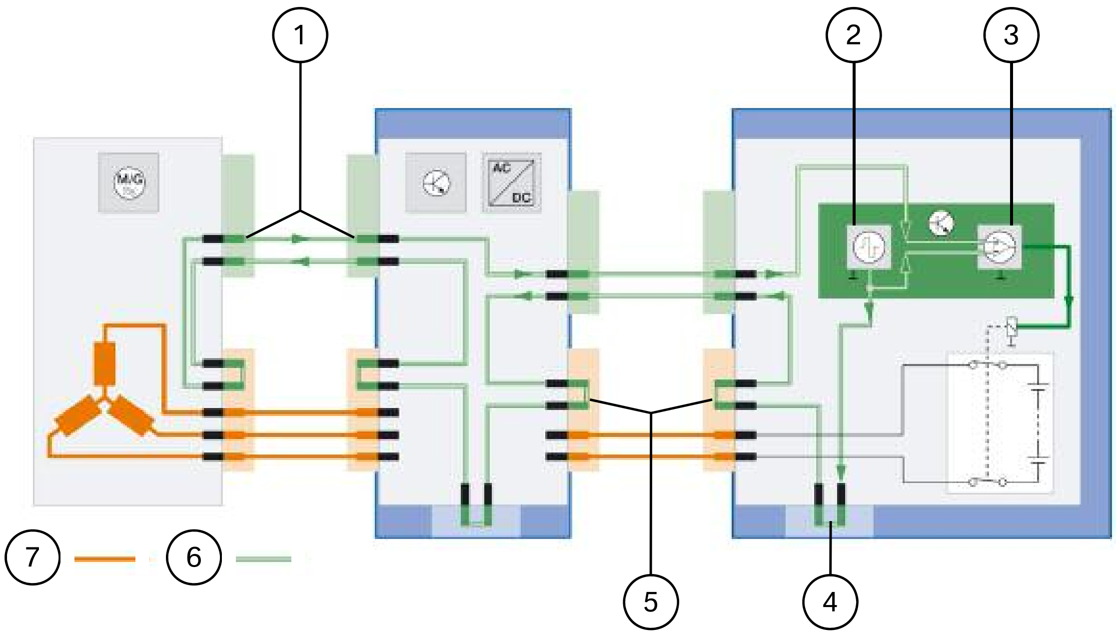
Principles of Hybrid Technology.

Safe working practices > Engineered safety measures > Safety covers on high voltage components

What's the purpose of the safety covers on high voltage components?

What happens when you remove a safety cover?

On which high voltage components can you find safety covers?



What are the major components of the high voltage interlock loop system?

1 ______________________

2 ______________________

3 ______________________

4 ______________________

5 ______________________

6 ______________________

7 ______________________

Under which conditions will the interlock signal be interrupted?
What happens, when the interlock signal is interrupted?

____

____

____

The electronics can be integrated as part of a control unit of a high-voltage component (for example the high-voltage battery). The generator and the evaluation circuit for the interlock signal can be split across two high-voltage components (e.g. high-voltage battery and power electronics).

Shutdown of the high-voltage system is automatic and takes place in several steps:

- Cancellation of activation signal for the electrical machine(s)
- Short-circuit of the coils of the electrical machines
- Opening of the switch contactors in the high-voltage battery
- Discharging of the high-voltage circuit.

In this way all possible voltage sources in the high-voltage system are reliably shut down. This ensures that no later than five seconds after interruption of the high-voltage interlock loop circuit there is no longer a hazardous voltage present at any point in the entire high-voltage system.

Discharge of the High-voltage Circuit

In addition to the high-voltage battery there are two other voltage sources in the high-voltage electrical system: the capacitors in the power electronics (and other high-voltage components) and coils of the electrical machines. Even after the switch contactors of the high-voltage battery open in the power-down process, the capacitors or the electrical machines would be capable of keeping the voltage in the high-voltage electrical system at a level high enough to constitute a touch hazard.

This is the reason why the high-voltage circuit is discharged each time the high-voltage system is powered down. The graphics on the next page uses a simplified circuit diagram of high-voltage components to illustrate how the discharge process takes place.

As long as the switch contactors of the high-voltage battery remain closed, the voltage of the high-voltage battery is present in the high-voltage cables. The capacitor on the DC voltage side of the power electronics carries the same voltage and is charged. The power electronics supply the high-voltage components with electrical energy, current flows through the high-voltage cables.

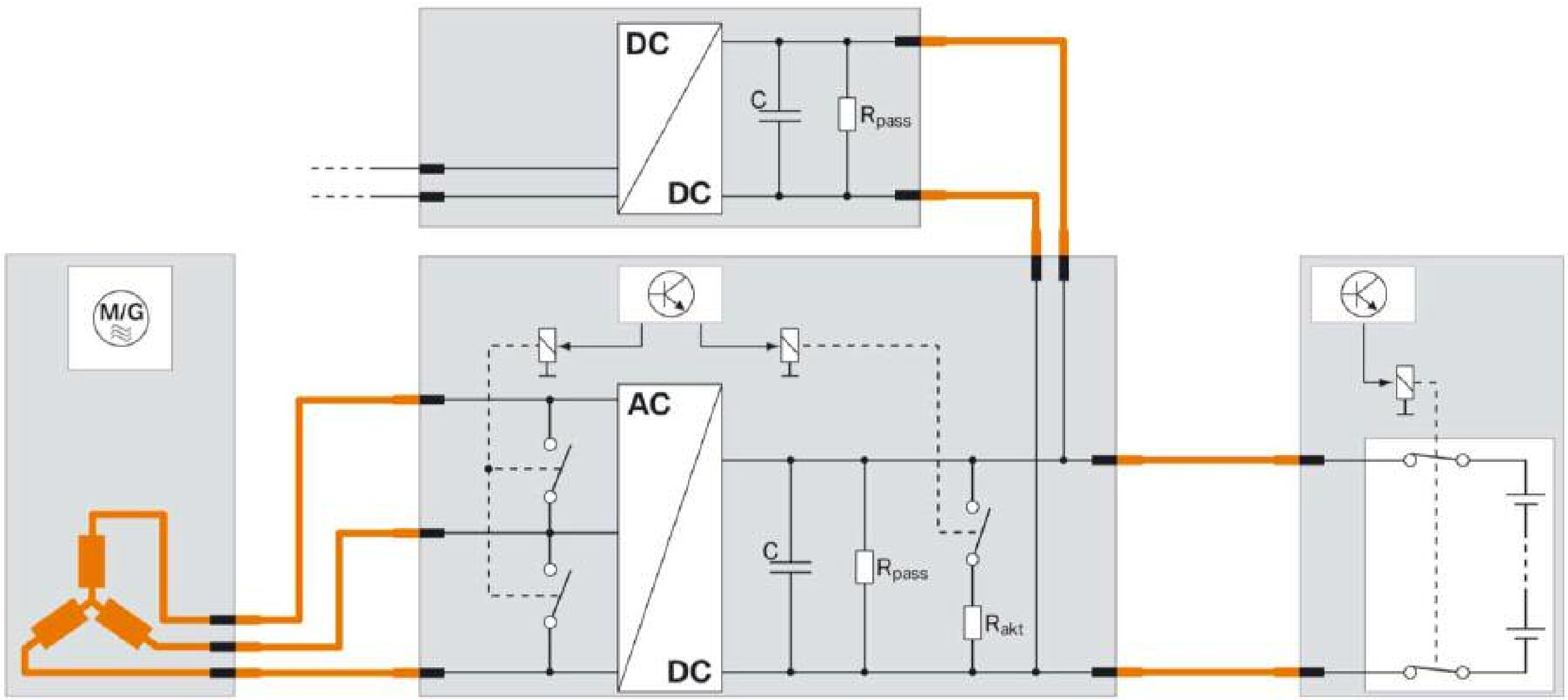
Before the switch contactors of the high-voltage battery are opened, the power electronics drive all the high-voltage consumers to assume a state in which they are unable to accept more current. In terms of the circuitry this state is equivalent to having no consumers connected to the high-voltage electrical system.

The electrical machines could still generate a hazardous voltage in the high-voltage electrical system, even if the switch contactors of the high-voltage battery have already opened. If the electrical machines were still rotating a voltage would be induced in their coils. This voltage would be applied to the high-voltage cables and depending on the speed of the electrical machines it could be of a level that would constitute a touch-contact hazard. To prevent this from occurring the coils of the electrical machines are short-circuited once the switch contactors of the high-voltage battery have opened.

Principles of Hybrid Technology.

Safe working practices > Engineered safety measures > Discharge of the high voltage circuit

What happens and in which sequence does it happen, when the high voltage system automtically shuts down?



Galvanic Separation Between HV and LV System

In hybrid vehicles the high-voltage electrical system and the 12 V vehicle electrical system are interconnected by a DC/DC converter. In this way it is possible for example to charge the 12-V battery using energy from the high-voltage electrical system. This means that a 12-V generator is no longer necessary.

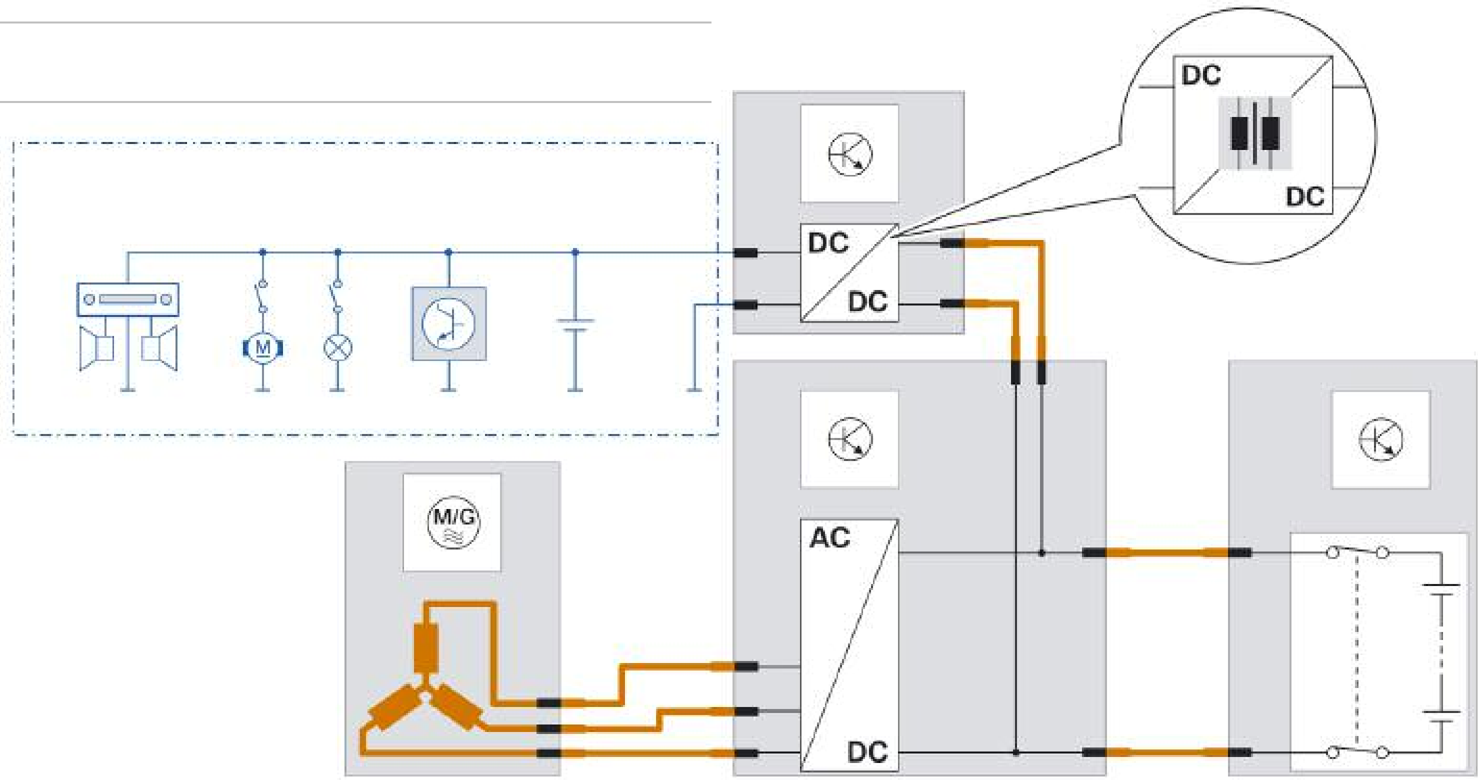
Despite the obvious advantages of this "energy-transfer" connection between the two vehicle electrical systems, safeguards have to be in place to ensure that hazardous voltage from the high-voltage electrical system cannot be transferred to the 12-V system. If this were not the case the 12 V vehicle electrical system would be subject to application of the same rules for electrical safety as apply to the high-voltage electrical system with regard to preparation for and work on the high-voltage electrics.

The 12 V vehicle electrical system and the high-voltage electrical system are galvanically separated, in other words there is no conductive connection between the two systems. This is accomplished by suitably insulating all the components and wiring. The DC/DC converter requires a circuit that ensures galvanic separation while sustaining the energy-transfer capability.

A circuit such as a transformer circuit is suitable in this respect. Energy cannot be transferred between two DC networks by a transformer, so the direct current voltages have to be transformed into AC voltages and vice versa.

There is an energy flow between the high voltage system and the 12 V system. But by which component is the galvanic separation implemented?

Take a look at the grounding of the 12 V system. Is there a chassis ground connection at the high voltage system? What are the consequences?



Short-circuit Monitoring

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

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

The consequences of these very high short-circuit currents would be severe. They range from arcing through irreparable damage to high-voltage cables or the high-voltage battery to fire. In order to avoid consequences of this nature, technical measures for the detection of a short circuit are engineered into the high-voltage electrical systems of hybrid vehicles. As a general rule, these measures are integrated into the high-voltage battery.

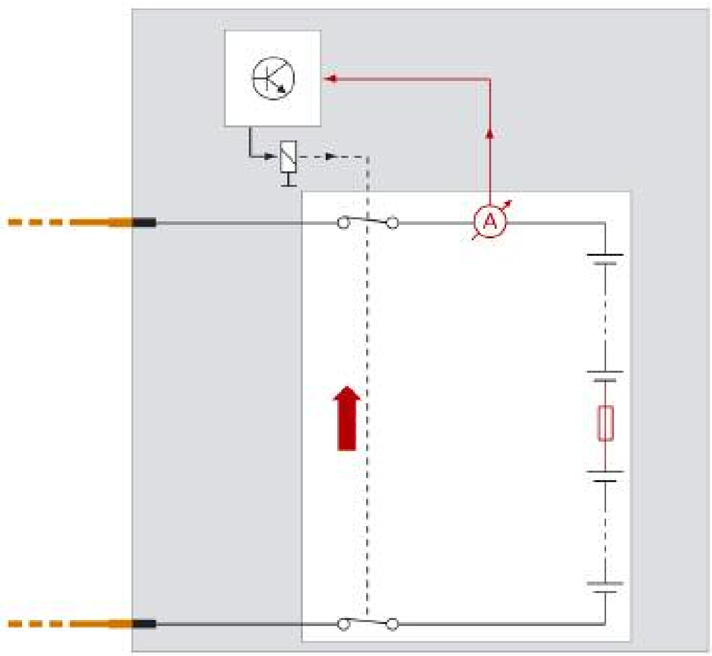
High-amperage safety fuses and electronic overcurrent trip breakers are used. To reduce the response time in the event of a short circuit, current is electronically monitored by current sensors in the battery cables.

If the control unit of the high-voltage battery unit detects an impermissibly high current, it triggers opening of the contacts of the switch contactor in the high-voltage battery. The switch contacts are designed to open reliably even despite the high currents that occur in a short-circuit event.

The downside of this design, however, is that the switch contacts are corresponding short-lived. Electronic short-circuit monitoring reduces response time with regard to conventional safety fuses, particularly when the currents involved are high.

Why do we need a "short circuit monitoring" of the high voltage system?

How does the "short circuit monitoring" work?



Shutdown in the Event of an Accident
If the vehicle is involved in an accident the high-voltage cables below the floor could be sheared off and this could cause sparking or arcing, if the bottom of the vehicle comes into contact with sharp-edged obstacles (e.g. crash barriers).

In order to minimize this risk the high-voltage system is deactivated in the event of an accident. In all current BMW vehicles and therefore in the BMW ActiveHybrid models as well, accident detection and the co-ordination of the safety systems are handled by the Crash Safety Module (ACSM).

If the Crash Safety Module detects a crash of corresponding severity, the 12-V battery's positive lead (BST) is pyrotechnically disconnected from the positive battery connection point. Along with the positive battery cable, in these vehicles the battery safety terminal interrupts another 12-V conductor. This conductor is used in two different ways to shut down the high-voltage system in hybrids:

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

The switch contactor contacts are opened without additional action on the part of the control unit in the high-voltage battery unit. The supply voltage for the electromagnet of the electromechanical switch contactor in the high-voltage battery unit receives its operating power directly from the BST circuit. If the supply voltage drops out, the contacts of the switch contactor automatically open.

The power electronics uses the 12-V cable interrupted by the battery safety terminal as a signal input for active discharge of the high-voltage circuit. Interruption of this cable triggers the control unit of the power electronics to:

- short-circuit the coils of the electrical machines
- initiate active discharge of the capacitors.

Triggering of the battery safety terminal is a signal in response to which the high-voltage system is shut down in the event of a crash. The Crash Safety Module's bus telegrams are also processed: as soon as the Crash Safety Module signals a crash of corresponding severity by means of a bus telegram, the high-voltage system is shut down.

These engineered-safety measures suffice to ensure that the high-voltage system is shut down reliably and in a very short space of time in the event of a crash. This virtually excludes the possibility of high-voltages presenting hazards in the course of or subsequent to a crash.

Nevertheless, it is important to bear in mind that special care always has to exercised when dealing with high-voltage components if the component housings have been damaged in a crash. In case of doubt, always contact BMW Group's Technical Support (PUMA).

Why is it important that the high voltage system shuts down automatically in case of an accident?

How is the shutdown triggered? How is the shutdown carried out?