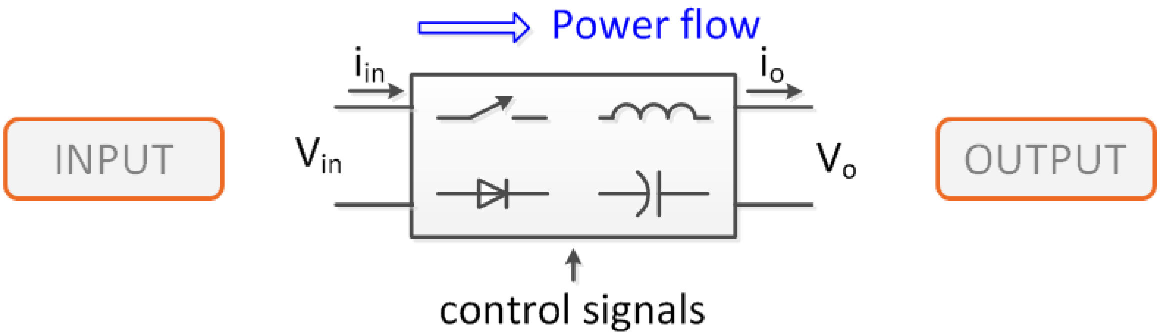
In his lecture, Professor Pavol Bauer explains all about how power is converted between the various power sources and power consumers in an electric vehicle. This is done using power electronic converters. A **power electronic converter** is an electronic device made of high power semiconductor switches that uses different switching states to change the magnitude and waveform of the voltage and current between the input and output.



Power semiconductors

Power semiconductor devices are widely used in automotive power electronic systems, and often dictate the efficiency, cost, and size of these systems. Active power semiconductor switches such as **MOSFETs** and **IGBTs** serve as load drivers for motors (ranging from 75 kW AC traction motors to 1W DC motors), solenoids, ignition coils, relays, heaters, lamps, and other automotive loads. Diodes are used in automotive systems to rectify AC current generated by the alternator, provide freewheeling current path for IGBTs or MOSFETs in DC/AC inverters and DC/DC converters, and suppress voltage transients. An average vehicle nowadays has over 50 actuators, which are often controlled by power MOSFETs or other power semiconductor devices.

The voltage ratings of power semiconductor devices are considerably higher than the specified maximum operating voltage or battery voltage of the power systems. This is because the voltage rating of automotive power electronics is mainly determined by the survivability of these devices to the commonly encountered overvoltage transients in the automotive environment, instead of just the maximum operating voltages. The transients on the automobile power supply range from the severe, high energy transients generated by the alternator/ regulator subsystem to the low-level noise generated by the switching of inductive loads such as ignition coils, relays, solenoids, and DC motors. A typical automotive electrical system has all of these elements necessary to generate undesirable transients. It is critical that automotive power semiconductor devices have sufficient voltage ratings to sustain these electrical transients. The current ratings of a power semiconductor are mainly related to the energy dissipation and the junction temperature in the device. The maximum continuous current is usually defined as the current that the device is capable of conducting continuously without exceeding the maximum junction temperature.

Commercially available power semiconductor devices can be categorized into several basic types such as diodes, thyristors, bipolar junction transistors (BJT), power metal oxide semiconductor field effect transistors (MOSFET), insulated gate bipolar transistors (IGBT), and gate turn-off thyristors (GTO). In addition, there are power integrated circuits (ICs) and smart power devices that monolithically integrate power switching devices with logic/analog control, diagnostic, and protective functions. Emerging device technology is SiC-based power devices. SiC is generally considered the most promising semiconductor material to replace silicon in future power electronic systems.

SiC power devices offer the following benefits over their silicon counterparts:

- The higher breakdown electric field strength of SiC allows a much thinner drift region and thus a much smaller specific on-resistance of SiC devices than their silicon counterparts.
- The low on-resistance of SiC devices for a voltage rating of 600–2000V allows the use of majority-carrier devices like MOSFET and Schottky diodes rather than minority-carrier devices such as IGBT and PiN diodes. This results in a much reduced switching losses and absence of charge storage effect. Lower switching losses will further allow higher switching frequency and subsequently smaller and less expensive passive components such as filter inductors and capacitors.
- The larger bandgap results in higher intrinsic carrier concentration and higher operating junction temperature. In principle, SiC devices could operate at a junction temperature as high as 300oC, as compared to 150oC maximum junction temperature of silicon devices. The increased operating temperature will reduce the weight, volume, cost, and complexity of thermal management systems.
- The very high thermal conductivity of SiC reduces the thermal resistance of the device die.
- The higher bandgap also results in much higher Schottky metal-semiconductor barrier height as compared to Si. This leads to extremely low leakage currents even at elevated junction temperatures due to reduced

thermionic electron emission over the barrier.The magnetic field from the stator will induce a voltage and current in the windings of the rotor. That's why it's called the induction motor. This in turn leads to the rotor producing its own magnetic field, and this magnetic field will make the rotor turn so as to align itself with the magnetic field from the stator. The rotor will follow this rotating magnetic field in the stator, without the need for a commutator with brushes.

Classification of power converters

There are four types of power converters:

1. DC-DC converter
2. DC-AC converter (or) inverter
3. AC-DC converter (or) rectifier
4. AC-AC converters

Further, power converters can be bi-directional or uni-directional; isolated or non-isolated. The three basic ways to classify a power converter are shown in the table below:

Type				
AC or DC	AC-DC	DC-AC	DC-DC	AC-AC
Magnetic isolation	Isolated		Non-isolated	
Bidirectional power flow	Bidirectional		Unidirectional	

Isolation between EV battery and grid

Isolation is necessary between the EV battery and the grid for safety reasons. Hence the AC/DC on-board charger and/or the DC/DC battery converter must be isolated. Depending on the EV, one or both of these converters are isolated and different power converter topologies are used.

Conservation of energy

In any power converter, energy is always conserved. Hence, the input and output power can be related based on the losses in the power converter as,

$$P_{out} = P_{in} - P_{loss}$$
$$P_{in} = V_{in} * I_{in}$$
$$P_{out} = V_{out} * I_{out}$$
$$\eta = P_{out} / P_{in} * 100$$

Where:

P_{out}, P_{in}, P_{loss} are the output and input power of the power converter

P_{loss} is the losses in the power converter

V_{in}, I_{in} are the input voltage and current of the power converter

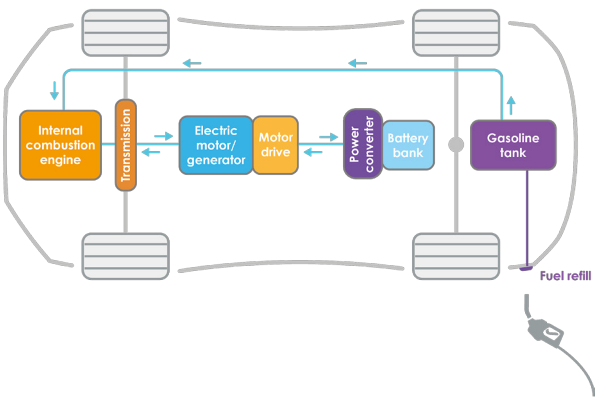
V_{out}, I_{out} are the output voltage and current of the power converter

Hybrid electric vehicle drivetrain

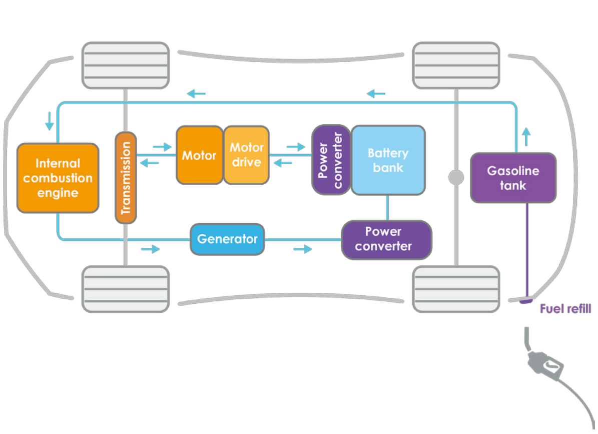
The electric drivetrain of an HEV can be envisaged to have the following components:

- Batteries as energy storage.
- DC-DC Converter for battery (bidirectional)
- DC-AC Converter for motor drive (bidirectional)
- Motor for driving
- Generator for charging battery from combustion engine
- Combustion engine (with powersplit)

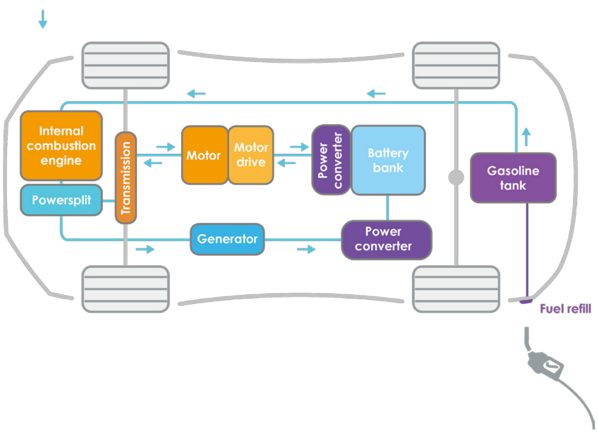
EV Parallel

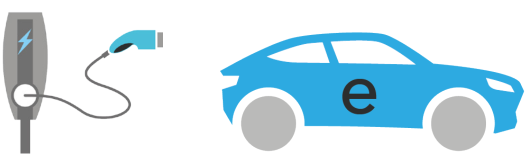


EV Series



EV Series-Parallel

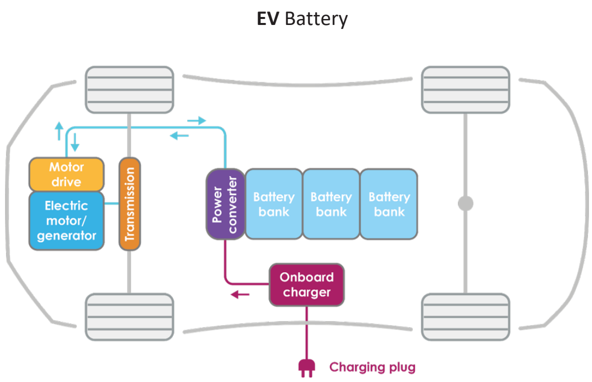




A typical electrical drivetrain of an HEV is shown in the figure above. Motor and generator is here separated. Generator is usually driven by the combustion engine. Typical voltages can be, for example, a battery voltage of 200 V, while the voltage of the DC link is 500 V. The link between the DC/DC power converter of the battery and DC/AC converters of the motor drive is called DC voltage link and contains as an energy storage a large capacitor.

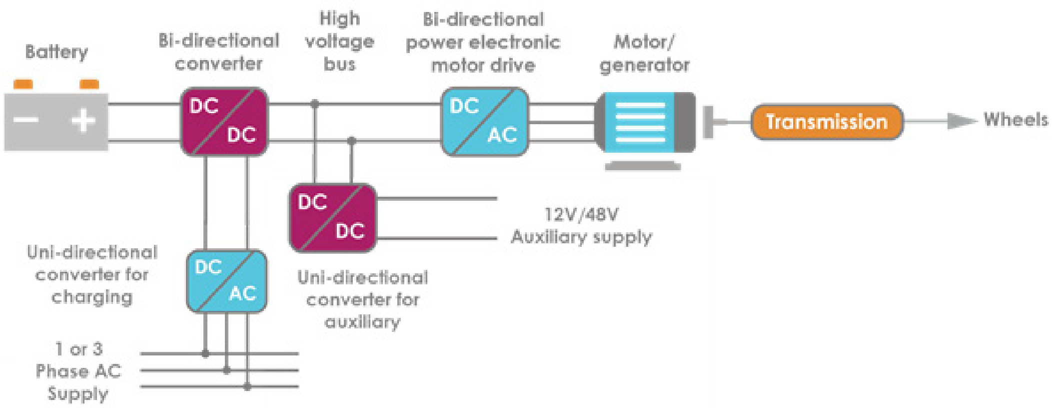
The used DC/DC battery power converter has to step-up (boost mode) the voltage in case of driving the car or accelerating while the battery is discharged. The energy flow is from the battery to the 500V DC link. On the other side by decelerating the energy is stored in the battery, the voltage of the DC link has to be stepped down (buck mode) and the energy flow is from the DC link to the battery.

Battery electric vehicle drivetrain

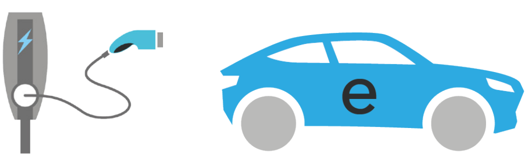


The electrical drivetrain of EVs shown in the figure above involves several conversion steps. It contains DC/DC converters, DC/AC as well as AC/DC converter. To regulate the power between the battery and the electric machines, it is necessary to use a power converter device. The battery is a DC supply source, delivering current at a particular voltage. Power flowing into the battery must be processed to ensure it is being delivered at the correct voltage. Similarly, the power delivered by the battery must be processed to ensure the electric machine can provide the optimum power to propel the vehicle.

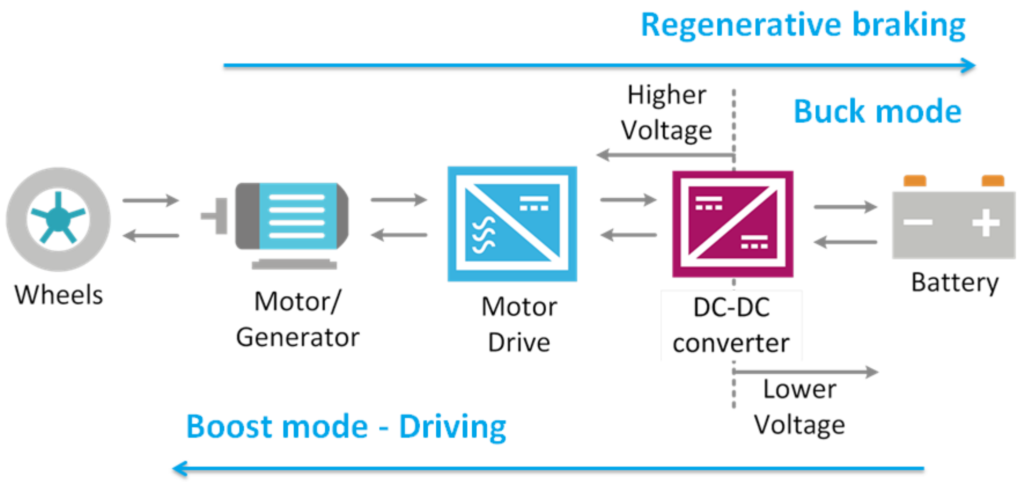
The precise functionality of power converters depends on many factors, but primarily on the type of electric machine being used and the maximum power delivery. Converters are made of high power fast-acting semiconductor devices, which act as high speed switches. Different switching states alter the input voltage and current through the use of capacitive and inductive elements. The result is an output voltage and current, which is at a different level to the input.



The figure above shows the typical layout of power electronics components in a Battery Electric Vehicle (BEV). The auxiliary supply provides the necessary power for equipment within the vehicle. This is usually 12V for current vehicles but may be increased to 48V for future vehicles. A three-phase induction motor or



a permanent magnet is typically selected to propel the vehicle. In general, the mechanical transmission is based on fixed gearing and a differential, but there are many possibilities for BEV configurations, depending on cost and performance constraints.



Buck and boost mode of operation for the battery DC-DC converter

The most common power processing DC/DC converter used for an EV is a step-up (boost converter) and step down (buck converter) as usually the battery voltage is much lower than the voltage of so called high voltage bus (see Figure). When recovering the kinetic energy from the vehicle, the device operates in buck (step down) mode, where the voltage level is decreased from the high voltage bus to a level that is within the safe voltage range of the battery. When propelling the vehicle, the device operates in boost mode and the DC voltage is regulated to output a higher voltage level for the electric machine. The conversion to different voltage levels is controlled by the controller, which uses the driver accelerator and brake pedals to select the operating mode. Further processing is required if an AC electric machine is used. The DC voltage must be inverted or rectified, depending on the direction of the power flow.

Equations for driving and braking

Kinetic energy ($\boldsymbol{E_{KE}}$ in Joules, J) of the car can be related to the mass of the vehicle (m in grams, g) and its velocity (v in meter per second, m/s):

$$E_{KE} = 1/2\, m\, v^2$$

v can be expressed in km/h units as well, where 1 m/s = 3.6 km/h.

$\boldsymbol{E_{KE}}$ can be expressed in kilowatt-hour, kWh or watt-hour, Wh units as well where 1 Wh= 3600J.

The energy (E_{ev} in Joules, J) delivered to the car by the drivetrain and the battery over a period t when delivering an average power (P_{ev} in Watts, W) when assuming there are no losses:

$$E_{ev} = P_{ev}\, t$$

The battery power P_{batt} can be expressed as a product of the voltage of the EV battery (V_{batt} in volts, V) and the charging/discharging current of the battery (I_{batt} in amperes, A) as:

$$P_{batt} = V_{batt} I_{batt}$$

Based on the EV battery power, the corresponding C-rate of the battery pack can be estimated.

C-rate is the ratio of the battery power (P_{ev} in kilowatts, kW) to the nominal energy capacity of the battery (E_{nom} in kilowatt-hour) in kWh. As the charging current increases, so does the C-rate:

$$\text{C-}rate = P_{ev} / E_{nom}$$

An alternate definition of C-rate is its the ratio of the battery charging/discharging current (I_{batt} in amperes, A) to the nominal ampere hour of the battery (Q_{nom} in ampere-hours, Ah):

$$C\text{-}rate = I_{batt} / Q_{nom}$$