Modul_2022

Electric and Autonomous Vehicles

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Introduction to electric vehicles and electrification of existing vehicles with IC engines

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DRIVEN

TABLE OF CONTENTS

1. ELECTRIC VEHICLE AND THEIR CLASSIFICATION

Electric Vehicle (EV) is a motor vehicle running entirely or partly on an electricity-powered drivetrain. Electricity is converted into mechanical energy by an electric motor, one or more of them, and the transformation of energy in the opposite direction is also made possible during the regenerative braking process, whereby part of the kinetic energy is converted into electrical energy instead of thermal energy. Depending on whether electric energy is used entirely or partially to drive the vehicle, as well as how this energy is obtained on the vehicle itself, there are several types of electric vehicles:

- *Battery Electric Vehicles (BEV)* are electric vehicles running entirely on an electricity-powered drivetrain. In these vehicles, the electricity used to drive the vehicle is stored in a battery pack which can be charged by plugging into the external electricity grid. During movement these vehicles have no exhaust emission;
- *Fuel Cell Electric Vehicle (FCEV)* are electric vehicles running entirely on electricity, but it is primarily obtained through fuel cells that use hydrogen stored under high pressure in the tanks on the vehicle itself as fuel. During movement these vehicles have no exhaust emission;
- *Hybrid Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV)* are electric vehicles that partially use electricity for their operation, i.e. they also use an internal combustion engine *(IC engine)* and an electric motor in different ways depending on the type of hybrid system (series, parallel, series-parallel, combined). Unlike hybrid electric vehicles *(HEV)* where electricity for electric motor propulsion and battery recharge is obtained exclusively by means of a generator powered by an internal combustion engine, in the case of plug-in hybrid electric vehicles *(PHEV)*, battery recharge can also be done from an external electricity grid, which significantly improves the possibility of using exclusively electric drivetrain. These vehicles, during the operation of the internal combustion engine, either for the purpose of propulsion of the vehicle or of the generator that recharges the batteries, emit certain amount of exhaust gases and cannot be considered *Zero Emission Vehicles (ZEV)*.

2. BATTERY ELECTRIC VEHICLE (BEV)

Battery electric vehicle is a motor vehicle running on an electric motor powered by an electrochemical source of electricity, i.e. its own battery. This electric vehicle does not pollute the environment by its operation and can therefore also be called a *Zero Emission Vehicle (ZEV)*.

Battery electric vehicle has a number of advantages over vehicles that have a IC engine due to the use of electric motor:

- No exhaust emission during vehicle operation;
- Noise level is multiple times lower;
- Operating vibrations are minimal;
- There are no problems with starting at low temperatures;
- Immediate drive availability with maximum torque;
- High energy utilization;
- Low maintenance costs;
- Low exploitation costs;
- The characteristics of the electric motor drive are extremely good and certain overloads are allowed;
- There is no dependence on petroleum products and it is possible to use domestic energy resources.

The electric drive also has certain disadvantages in relation to vehicles with a classic drive:

- Lower autonomy;
- Higher vehicle mass and less free space due to batteries;
- Slow recharge of batteries;
- The necessity of having a electricity grid for battery recharge.

2.1 HISTORY

At the world exhibition in Berlin in 1879, the company *Siemens* presented the first usable example of an electric vehicle on rail tracks, which could pull three smaller coaches with passengers. Already in 1881, a tricycle was driven in Paris, the motor of which was powered by lead batteries. Only a year later the horse-drawn tram was converted to electric-drive tram. A few years later, Thomas Edison constructed one of the first high-performance electric cars with nickel-alkali batteries that powered an electric motor with approx. 3.5 kW.

Immediately thereafter, an electric bus was constructed. In England, in 1888, John Camp Starley built a small electric car. In 1894, the company *Electric carriage and wagon co.* from Philadelphia started the production of these vehicles for commercial purposes, and in 1897 delivered a number of electric taxis to the city of New York (Figure 2-1.).

In Europe, the first electric vehicle was constructed by the French, Charles Jeantaud and Camille Alphonse Faure in 1881. The motor power was between 2.2 and 2.9 kW, and 200 Ah battery packs were placed in the rear of the vehicle and weighed 420 kg.

A special event in Europe occurred on May 1, 1899 when a torpedo-like electric vehicle called "Never Satisfied" *(Jamais Contente)* reached a speed of 100 km/h (Figure 2-2.). The vehicle weighing 1800 kg was constructed by the Belgian Camille Jenatzy.

Statistics show that in 1900, of approximately eight thousand cars on the roads of America, as many as 38% were electrically powered. The remainder were vehicles that used a steam engine and an IC engine drive.

The low autonomy of movement between the two charges was considered the biggest disadvantage of electric vehicles from that period. At the end of the 19th century, the specific energy in battery packs was approx. 10 Wh/kg. At the beginning of the 20th century, a value of 18 Wh/kg was reached, while only a decade later it was 25 Wh/kg. In addition, the network of charging stations was not sufficiently branched, although the situation began to improve at the beginning of the 20th century.

2-1. Figure Electric taxi vehicle by Electric Carriage and wagon co.

However, the oil sources discovered caused a low price of gasoline, and the advancement of technology in the production of IC engines created conditions for faster advancement of the cars that used these engines. Consequently, the development of electric cars remained aside.

In the mid-1960s, electric vehicles became popular again for a number of reasons: growing traffic congestion, atmospheric pollution and fear of the oil crisis. In addition, great progress has been made in the production of lead-acid batteries, which have become lighter and larger in capacity, so that the renaissance of electric vehicles begins in the 1970s. In 1974, the American company *Sebring-Vanguard* began small-scale production of an electric vehicle on a production line. Their 970 kg two-seater *CitiCar* with 48 V electric motor and 2.5 kW power achieved a top speed of 45 km/h (Figure 2-3.). The upgraded variant of this vehicle achieved a top speed of 60 km/h, while the vehicle covered up to 75 km with a single battery charge, and cost about USD 3000 (current value 15000).

Given the primary role of electric vehicles, most were relatively modestly equipped, until 1979, when *Electric Auto* from Michigan made the first luxury electric vehicle called *SilverVolt*. The prototype of this 5-seater vehicle achieved a top speed of 110 km/h with a radius of travel of 160 km between two battery charges. *SilverVolt* also had an air conditioner and sold for approximately US $15,000 (current value: US $50,000).

2-2. Figure
Electric vehicle "Never Satisfied" with a speed of 100 km/h (1899)

2-3. Figure
The first serial-production electric vehicle in XX century - CitiCar

In 1996, *General Motors* introduced the *EV1* (Figure 2-4.), the first serial-production electric vehicle that met the performance requirements of the driver. The vehicle had an asynchronous electric motor and an inductive charger. *EV1* accelerated from 0 to 100 km/h in 8 s, and its maximum speed was 160 km/h. The first model from 1996 used lead-acid batteries with a capacity of 53 Ah and a voltage of 312 V, which allowed a radius of movement of up to 100 km. The second-generation model (1999-2003) used nickel-metal hydride (NiMH) batteries, which reduced the weight and increased the radius of travel by up to 240 km. The set of 26 batteries, with a capacity of 77 Ah, is combined into single unit with a total capacity of 26.4 kWh.

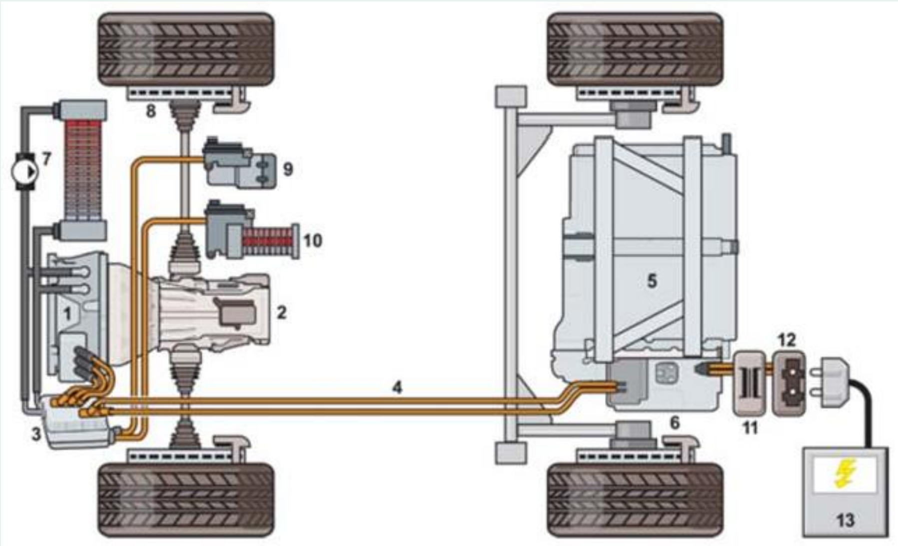
2-4. Figure
Electric vehicle General Motors EV1

2.2 ELECTRIC DRIVETRAIN COMPONENTS AND ITS STRUCTURE

The basic components of the electric drivetrain in the general case are: electric motor, batteries with recharging system, electronic control unit and transmission system. The aforementioned basic components together with the accompanying elements are functionally interconnected and make an appropriate structure of the electric vehicle which in general case might look like shown in Figure 2-5. The greatest differences in relation to the above general structure are the presence and method of operation of transmission system, which will be explained in more detail below. The aforementioned basic components are specifically covered below.

2.2.1 ELECTRIC MOTOR

An electric motor is an electric machine that uses electrical energy to produce mechanical energy, mainly through the interaction of a magnetic field and a conductor through which an electric current flows. The production of electricity from mechanical energy, as a reverse process, is performed by a generator. The fundamental principle of operation of an electromagnetic motor is the occurrence of an electromagnetic force that acts on the conductor through which the electric current flows, which is in the magnetic field, i.e. the induction of an electromotive force in the circuit that moves through the magnetic field. The conversion of mechanical energy into electrical energy and vice versa occurs only when the conductor performs relative movement in the magnetic field. The electric motor contains two basic parts, a magnetic part (core of ferromagnetic material) and an electric part (one or more windings). Electric motors are constructed from two parts, namely a stationary part, called a stator, and a movable part, called a rotor. There is a clearance between the stator and the rotor that allows movement, because an electromagnetic field is induced in it. The effect of the stator electromagnetic field on the rotor windings leads to creating a torque.



2-5. Figure Electric drive structure with basic and supporting components

1 - electric motor

2 - transmission system

3 - electronic control unit for electric motor operation (controller)

4 - electrical current conductors

5 - battery

6 - inverter with electronic control unit for battery operation and charging

7 - cooling system

8 - braking system (including regenerative)

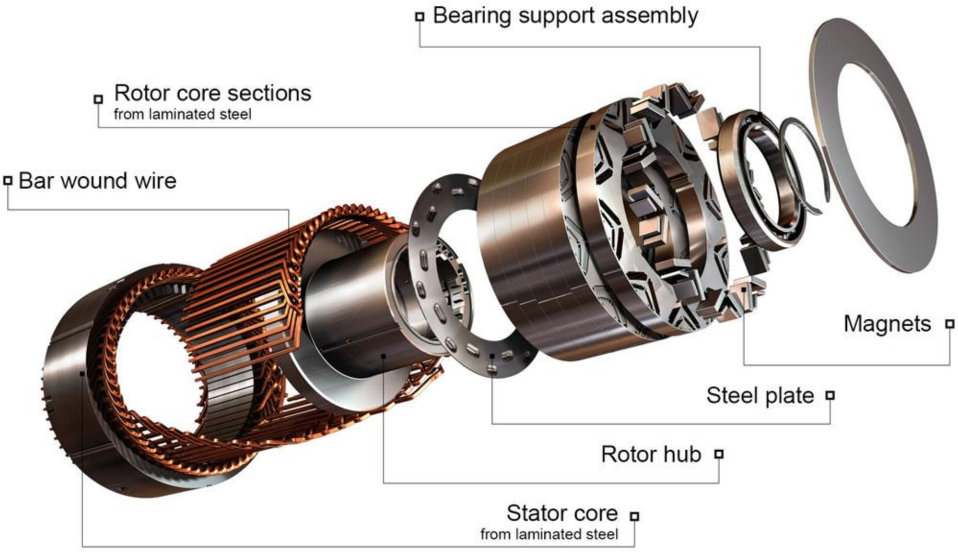
9 – high-voltage compressor of air conditioner

10 – heating system

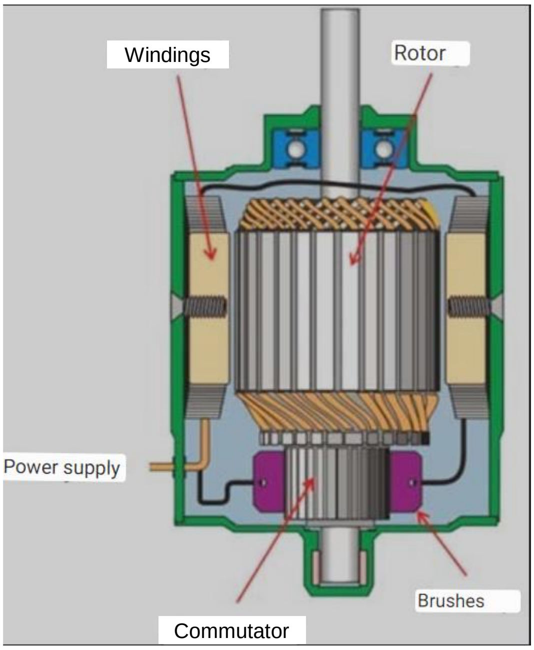
11 – battery charger

12 – charging connector

13 – external source of electricity to recharge the battery



2-6. Figure
Three-phase alternating current motor with permanent magnet



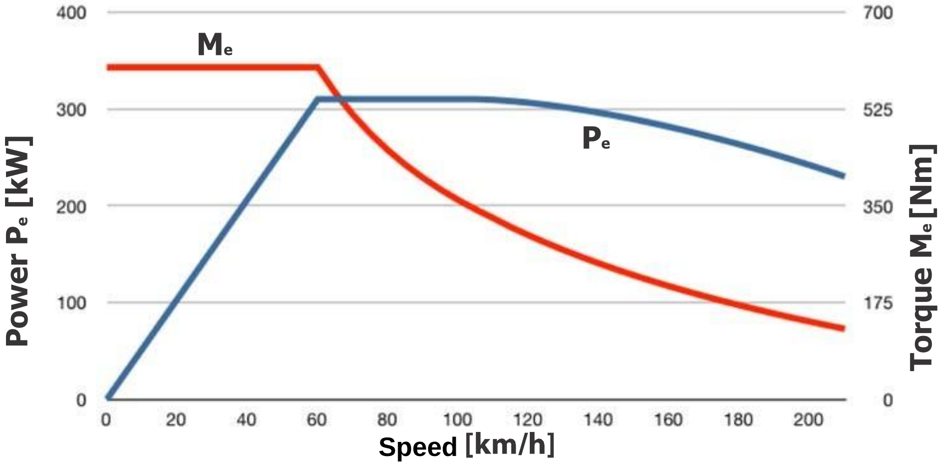
2.7. Figure
DC motor with brushes

The basic principle of operation is presented, which is essentially the simplest way of electric motor operation. With regard to the mutual position of the stator and rotor, various embodiments are possible. In most electric motors, the rotor is located inside the stator and rotates in it, but there are other variants. In addition, there are electric motors powered by direct or alternating current, as well as those that are synchronous or asynchronous. Bearing in mind the above constructive differences, but also those in the operating mode and characteristics, there are several different classifications of electric motors that will not be discussed here. It is important to point out that electric vehicles, in addition to a very large number of motor versions, usually use three-phase alternating current motors, namely induction (asynchronous) motors and synchronous motors with a permanent magnet (Figure 2-6.), as well as direct current motors that use brushes for operation (Figure 2-7.) or do not use them (with the permanent magnet excitation).

The choice of the electric motor is very important step and depends on the desired performance, the vehicle concept and the characteristics of the battery itself. Permanent magnet motors are becoming more and more common in the choice of drives due to the high current density, i.e. favorable characteristics of power and compactness, although their control algorithms are complicated. On the other hand, direct current motors are easier to install and more affordable, they are more suitable for short-term accelerations to lower speeds. The disadvantages are reflected in the increase in temperature during operation and the possible uncontrolled increase in the number of revolutions, as well as the poor characteristics in the generator mode. Due to these disadvantages and better characteristics for the same size and mass, said alternating current motors have the advantage. In any case, the requirements to be met by the electric motor are:

- High efficiency in high rpm range, especially in regenerative braking mode;
- High torque values at low rpm and high power at higher speeds or cruise speeds;
- High range of speeds with appropriate torque characteristic;
- Low mass and volume for required power;
- Adequate voltage regulation for a large range of rpm change,
- High reliability and operation in difficult conditions;
- Small price and easy maintenance;
- Low noise;
- Minimum cooling needs;
- Application of the modular assembly principle;
- Low level of electromagnetic noises;
- Resistance to water, shocks and dust.

What is common for all electric motors is a much higher efficiency (up to 96%) compared to IC engines (35 - 40%). An advantageous torque characteristic of electric motors compared to conventional IC engines has already been pointed out. The torque of the electric motor is the highest at the lowest rpm, which is of great importance when vehicles begin to move, as well as when driving uphill. An example of the torque characteristics of a *Tesla Model S* vehicle is shown in Figure 2-8.



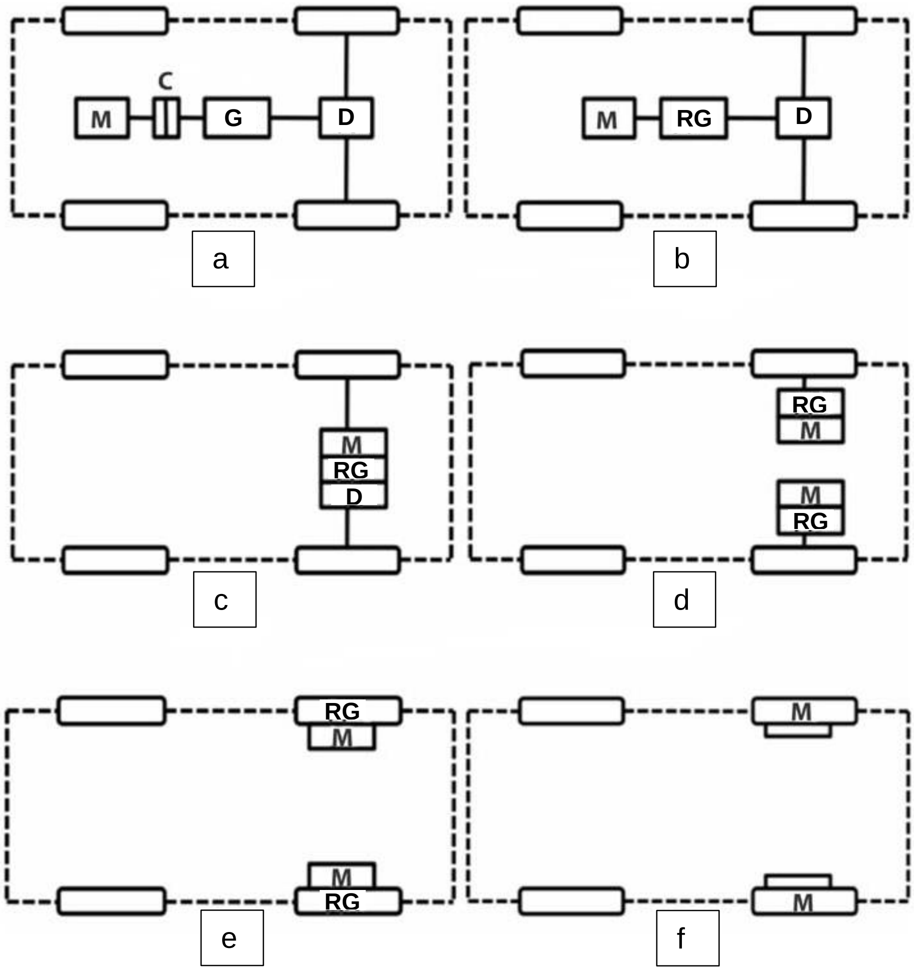
2-8. Figure
External characteristic of the drivetrain in Tesla Model S

2.2.2 TRANSMISSION SYSTEM AND DRIVETRAIN STRUCTURE

There are several solutions for the structure of the electric vehicle drivetrain, i.e. the transmission that connects the electric motor to the drive wheels. From the solution that is the most similar to a classic IC-engine vehicle, which implies the existence of an electric motor connected via a coupling to a multi-stage transmission, to the solution where the wheel has its own drivetrain, which enables its independent propulsion, whereby power transmission elements are not required. Whether the vehicle will have a gearbox with several (two or three) gears or only a reduction gear with a constant transmission ratio depends on the purpose and desired performance of the vehicle, i.e. the available torque and power for the designed acceleration, maximum speed and road resistance, but also on the characteristics of the electric motor itself. In these cases, with one electric motor, the existence of a differential transmission and drive axle shafts is mandatory, while in the case of electric motors per wheel, these elements are unnecessary.

Figure 2-9. shows possible electro-drive structures with appropriate transmission. The case under a) shows a variant of an electric vehicle in which the transmission is substantially the same as in conventional vehicles powered by a IC engine. b) shows a variant in which there is no main clutch and a gearbox, but only one supplementary transmission with a fixed transmission ratio (reduction gear). The advantage of such a transmission is lower weight of the vehicle, which necessitates a more complicated electric motor control system in order to provide the required torque.

The case under c) is essentially indistinguishable from the case under b), but in this variant the motor, the reduction and the differential gear form a single assembly. This variant is also shown in Figure 2-10. A variant with two drive motors is shown under case d). In this configuration, the difference between the number of revolutions of the left and right wheels is ensured by electric control of the motor. In order to avoid mechanical transmission of power, and therefore to reduce losses, electric motors can be installed in the wheels (Figure 2-11.). e) shows a concept where, in addition to the motor in the wheel, there is also a reduction gear in order to provide greater torque. Due to the high angular velocity of the electric motor, its compactness and the possibility of alignment of outputs and inputs in such cases, planetary gearset is always used.



2-9. Figure
Possible structures of electric drivetrain with appropriate transmission

M – electric motor

C – clutch

G – gearbox

RG – reduction gear

D – differential gear

2-10. Figure
Chevrolet Spark EV electric drive transmission system

2-11. Figure Chevrolet Spark EV electric drive transmission system

The last case (f) also shows a variant with a motor in the wheel but without any mechanical gears. In such cases, slightly different electric motors and significantly more complex algorithms for their control are used. The same principle is also applicable to the wheels of the second axle, thus obtaining a system with all-wheel drive.

2.2.3 BATTERIES OF ELECTRIC VEHICLES

There are several different types of batteries used for storing electricity, depending on the manufacturing technology and characteristics, some are smaller and some are more represented in electric vehicles. When selecting the battery, it is necessary to take into account safety, resistance to vibration and large temperature differences and behavior when fully depleted, when a large amount of electricity is needed per unit of time.

At the beginning of the development of electric vehicles, lead-acid batteries were the most prevalent, and later nickel-cadmium batteries. The basic advantages of lead-acid batteries are relatively simple production and a low price. However, the disadvantages of this technology are particularly pronounced when these batteries are used as traction batteries, as they are not sufficiently resistant to variable operating temperature and vibration during exploitation. Also, the specific weight relative to the battery capacity is high.

Increased number of electrical devices has resulted in further advances in technology in this area, i.e. The development of nickel-cadmium *(NiCd)* batteries that have found wider application in portable power tools and lighting devices. Although this rechargeable battery technology was more expensive to manufacture, it was also used in the first modern electric vehicles in the late 70s and 80s of the last century. The main reason is greater resistance to vibration and temperature variations during exploitation. In addition, these batteries are designed to withstand “full” depletion during use. The most significant advantage of these batteries over lead ones is a considerably higher density of accumulated energy, while the biggest disadvantage is the so-called memory effect when recharging. Another disadvantage of nickel-cadmium batteries is the occurrence of self-discharge while they are not in use.

The emergence of a large number of portable devices during the last two decades of the last century, has accelerated the development of batteries. The second generation of battery systems can be divided into two basic categories, which are batteries intended for use in consumer devices, which have found application in electric vehicles as well, and batteries for special purposes. The category of consumer batteries includes nickel-metal hydride *(NiMH)*, lithium-ion *(Li-Ion)* and lithium-polymer batteries *(Li-Po)*, and the category of special purpose batteries includes lithium-ferrophosphate *(LiFePO4)*, lithium-nickel-manganese-cobalt *(LiNiMnCo)*, molten-salt batteries *($NaNiCl_2$)*, zinc-air *(Zn-Air)* and vanadium redox battery *(VRB)*. Of the listed types, only some are usable for electric vehicles, so only these will be presented in greater detail.

Nickel-metal hydride batteries have replaced nickel-cadmium batteries in most applications. The advantage is reflected in the attenuated memory effect and the lower tendency towards self-discharge with a slight increase in the energy density that they are able to accumulate. Another significant advantage is that they are significantly more environmentally friendly, because cadmium is a very toxic substance.

2-12. Figure
Cross-section of vehicle lithium-ion traction battery

Lithium-ion batteries (Figure 2-12.) were revolutionary for portable devices thanks to their low weight and the ability to be produced in various shapes. Another advantage of lithium-ion batteries is the complete absence of memory effect. This type of battery consists of a negative electrode (the most common material is carbon, i.e. graphite), a positive electrode that is produced from a metal oxide and an electrolyte consisting of a lithium salt in an organic solvent. The electrochemical role of the anode and the cathode, i.e. the two said electrodes, changes depending on the direction of movement of the current through the cell. The direction of movement of the current changes depending on whether the process of charging or discharging the battery is in progress. During the discharge, lithium ions *(Li+)* transfer current from the negative electrode towards the positive electrode. Charging is carried out with an elevated voltage of the same polarity as of the cell voltage during discharge. During the battery charging process, under the effect of the

charging voltage, the lithium ions move from the positive electrode to the negative electrode.

The mentioned types of batteries, such as lithium-ferro-sulfate, lithium-nickel-manganese-cobalt and lithium-polymer, are according to their chemical composition, structure and operating mode, actually the lithium-ion batteries. Their names derive from the oxide of the metal used as a positive electrode and from the substance used as an electrolyte. Thereby, the lithium-polymer battery is the only type that uses electrolyte in solid form. Depending on the materials used for batteries, the characteristics of these batteries also change significantly. One of the negative characteristics of lithium-ion batteries is that they can be dangerous, because at high temperatures a reaction occurs that can cause fire or emit dangerous gases. Therefore, each cell is connected to an electronic circuit that monitors the voltage, minimum and maximum temperature and, if necessary, limits the charging or discharging current. The existence of this electronic circuit leads to the self-depletion of cells, that is, energy consumption due to the operation of the said circuit.

BATTERY TYPE	Pb	NiCd	NiMH	Li-ion
Nominal cell voltage [V]	2	1.2	1.2	3.6
Energy density [Wh/kg]	35	50÷80	70÷95	118÷250
Specific power [W/kg]	180	200	200÷300	200÷430
Monthly self-depl. [%]	<5	10	20	<5
Number of charging cycles	1000	2000	<3000	2000
Operating temperature [°C]	-15÷50	-20÷50	-20÷60	-20÷60
Costs of production [$/kWh]	60	250÷300	200÷250	150
BATTERY TYPE	Li-Po	LiFePO4	Zn-air	ZEBRA
Nominal cell voltage [V]	3.7	3.2	1.2	3.6
Energy density [Wh/kg]	130÷335	120	460	90÷120
Specific power [W/kg]	260÷450	2000÷4500	80÷140	155
Monthly self-depl. [%]	<5	<5	<5	<5
Number of charging cycles	>1200	>1200	200	>1200
Operating temperature [°C]	-20÷60	-45÷70	-10÷55	245÷350
Costs of production [$/kWh]	150	350	90÷120	230÷345

2-1. Table
Basic characteristics of different types of batteries used in electric vehicles

Batteries based on molten salt technology use sodium as a negative electrode. Sodium is suitable due to its low mass, is non-toxic and readily available in nature. The sodium used in these batteries is in liquid form. Since the melting point of sodium is 98°C, batteries of this type usually operate at temperatures above 250°C, which makes them high-temperature batteries. The battery that uses the described molten salt technology, thus forming a special subgroup, is the so-called *ZEBRA (Zeolite Battery Research Africa Project).*

Table 2.1 gives the basic characteristics of the different types of batteries used in electric vehicles.

2.2.4 MOTOR CONTROL UNIT – CONTROLLER

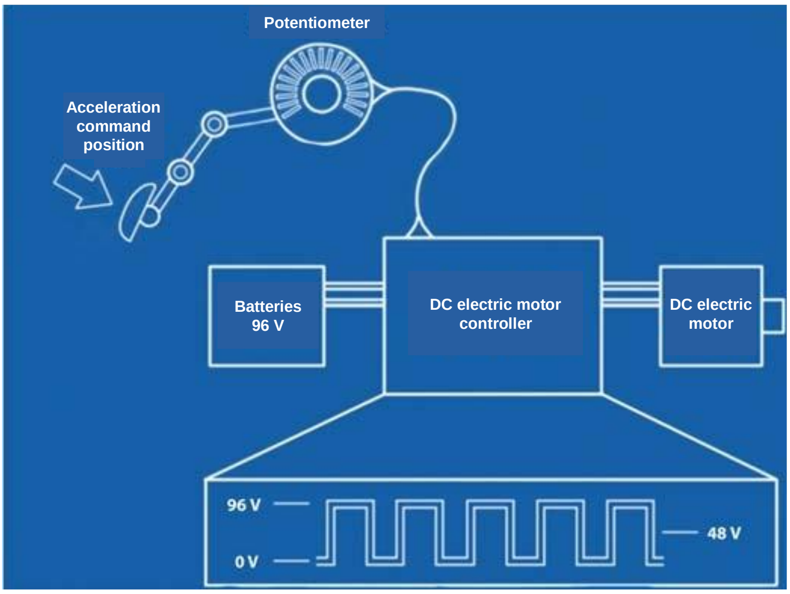
The electric motor control unit, commonly known as the controller, is a very important component for the operation of an electric vehicle. The controller controls the electric motor by regulating the parameters of the electric current supplied to the motor based on the position of the acceleration command (“accelerator pedal”), whereby the necessary power must be provided to overcome the resistance of movement. In the case of alternating current motors, the direct current of the high-voltage battery must be transformed into alternating current by means of an inverter, while in the case of direct current motors the value of its voltage must be adjusted.

The controller also provides a regenerative braking function to convert the vehicle's kinetic energy into electrical energy, rather than permanently losing thermal energy. During regenerative braking, the electric motor stops consuming electricity, but continues its operation as a generator by producing it. Regenerative braking is most effective in maintaining downhill speed and low intensity deceleration, while in more intensive braking the classic braking system is activated.

The basic function of all controllers is reflected in the fact that the desired speed of movement of the vehicle is achieved by the most efficient operation of the electric motor with the available amount of electricity. However, the operating mode and complexity of the controller depend on the type of electric motor applied.

Thus, for example, controllers for three-phase and single-phase induction motors, or alternating current electric motors, use technology that controls its angular velocity and power by changing the frequency of the voltage. So, by changing the frequency of the voltage the motor angular velocity will increase or decrease, i.e. the vehicle will accelerate or slow down.

Controllers for direct current motors operate on a simpler principle. One reason is the fact that the angular velocity of the rotor is proportional to the value of the voltage, and the other is that the change in the direction of movement is achieved by simply changing the polarity of the voltage. The DC motor control scheme is given in Figure 2.13. The acceleration command (“accelerator pedal”) is connected via a potentiometer to the controller which, in the event of the end position of the command (maximum acceleration), allows the flow of the electrical current of the maximum voltage (in the above example, this voltage is 96 V), while in the case when the command is not activated, this voltage is 0 V. In any intermediate position of the acceleration command, the controller will allow the flow of current to the motor in pulses so that the average value of the voltage corresponds to the position of the command (if that position is e.g. 50% of the maximum, the average value of the voltage of the supplied current will be half of the maximum value, thus 48 V). The disadvantage of using direct current motors without a permanent magnet in the stator is the inability of regenerative braking.



2-13. Figure
Control scheme for direct current motors

However, the controllers for brushless DC motors (with the permanent magnet excitation in the stator) are much more complex, but the regenerative braking function can be used. In addition, these motors are placed in the wheel so that the angular velocity of the motor is equal to the angular velocity of the wheel. This means that the controller can also have functions that are in classic vehicles performed by additional devices for traction control and torque distribution such as anti-lock braking systems, stability control, traction control, etc.

Regardless of the type of motor, controllers often have additional functions that inform the driver and other vehicle systems about the operating parameters of the engine, temperature, electricity consumption, operating voltage, speed and remaining vehicle autonomy.

2.3 EXAMPLES OF ELECTRIC VEHICLES

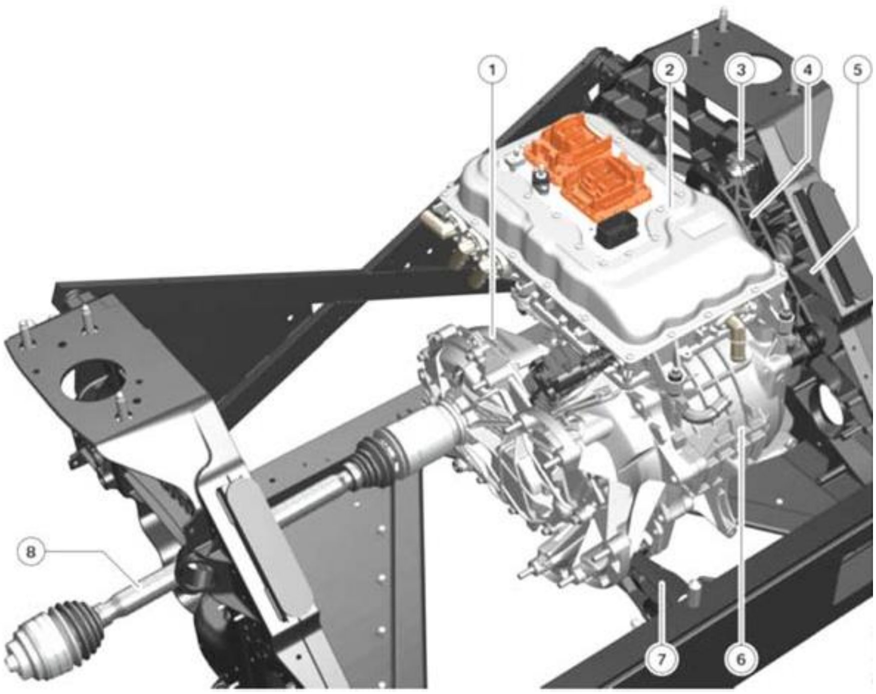
2.3.1 BMW i3

The *BMW i3* is an example of a modern electric car that has been serially produced since 2013. Its advantages are reflected both in the environmentally friendly operation and in the application of modern materials, which significantly reduced the total mass of the vehicle. The ecological approach was also applied in the production process of the above model, bearing in mind that the factory in Leipzig (Germany) is one of the most modern. Water consumption decreased by 70% and total energy consumption by 50% compared to other factories of the same producer and capacity. Modern, fully automated material bonding technology, absence of welding sparks and noise in forming screw connections and riveting are just some of the features of the manufacturing process. Manufacture of carbon fibres, which are used for production of a bodywork, requires a very large amount of electricity, so it is located on Moses Lake (northwestern United States of America), where the largest hydroelectric power plant in the world is located.

2-14. Figure
Structure of the BMW i3

Great attention has been paid to reducing the total mass so that the vehicle, despite the presence of the battery, has a mass in the range corresponding to that class of vehicle, which is 1195 kg. Figure 2.14 shows the structure of the *BMW i3* vehicle, where a carbon fibre body can be seen, an aluminum chassis that also protects the battery compartment, while the drivetrain is located in the rear of the vehicle. Thermoplastic is used as a material for all body surface elements except the roof which is made of carbon fiber. Lithium-ion batteries with a nominal voltage of 360 V and a capacity of 22 kWh are located in the floor of the vehicle and are protected by the structure of the aluminum chassis, which significantly reduces the height of the centre of gravity.

The vehicle drive is provided by a synchronous alternating current motor with a permanent magnet with a maximum power of 125 kW and a torque of 250 Nm, which is immediately available when the vehicle starts to move. The electric motor can achieve 11000 rpm, while the transmission ensures a constant reduction in the number of revolutions in the ratio of 9.7:1. The electric motor has a mass of only 49 kg, while the average IC engine for this class would weigh 160 kg. Figure 2.15 shows the structure of the vehicle drivetrain with all its elements.



2-15. Figure
BMW i3 drivetrain structure with basic elements

1 - single-stage transmission with a transmission ratio of 9.7:1

2 - controller with inverter

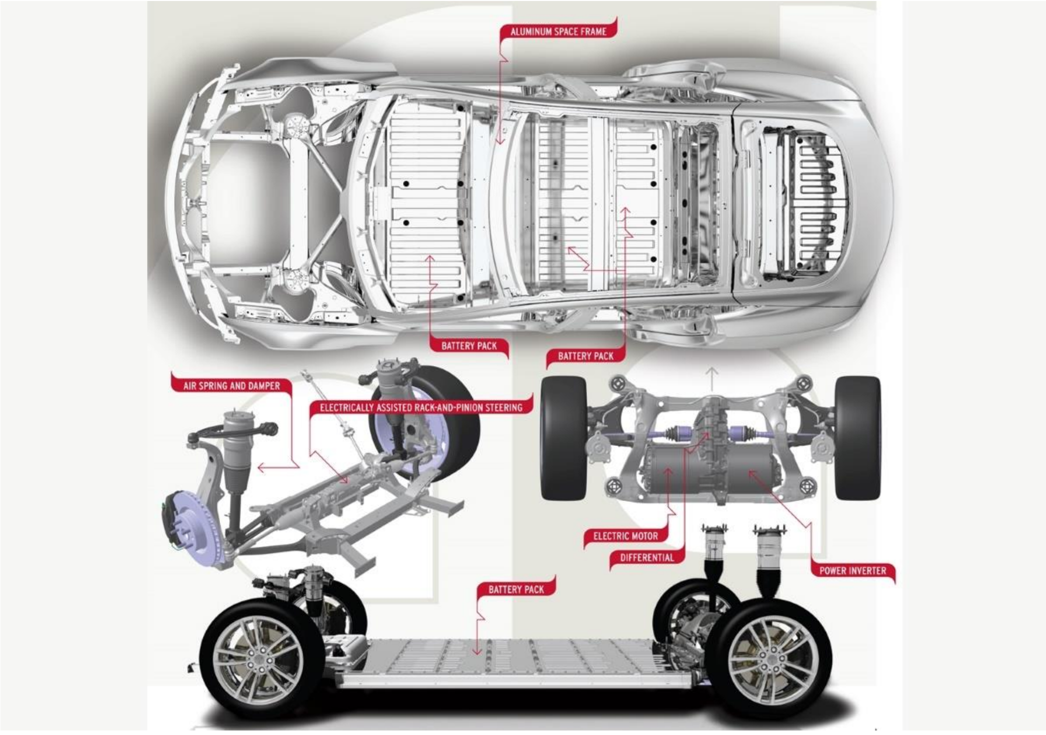
6 - electric motor

8 - drive axial shaft

The *BMW i3* achieves the following performance: acceleration from 0 to 100 km/h in 7.2 seconds, acceleration from 80 to 120 km/h in 4.9 seconds and a top speed of 150 km/h. Under average driving conditions, a vehicle with a single battery charge can travel from 130 to 160 km, which corresponds to an average charging period of 3 to 5 days. In the most energy efficient mode, autonomy can be up to 200 km. With zero exhaust emissions, the average electricity consumption is 12.9 kWh / 100 km.

It should be pointed out that there is a variant of the *BMW i3* with an additional two-cylinder IC engine, whose operation drives the battery recharge generator. In this way, the vehicle becomes a classic series hybrid with greater autonomy of movement than a variant with entirely electric drive.

2.3.2 TESLA MODEL S



2-16. Figure
Vehicle structure of Tesla Model S

Tesla Model S is a vehicle that widely promoted electric drive in the segment of luxury sports vehicles. The first generation of this car was introduced in 2009, and has been refined several times so far, and there are several variants regarding the battery energy and type of drive (rear-wheels or all-wheel drive). The low value of the air resistance coefficient ($c_x = 0.24$) and the use of aluminum in the production of the bodywork has contributed to the vehicle not only having a sporty appearance, but also adequate performance. Regarding the energy of the battery, there are variants of 40, 60, 65, 70, 75, 85, 90 and 100 kWh (currently 75 and 100 kWh variants are available for purchase). In addition to the rear-wheel drive, all but the first variant has the all-wheel drive version, which is achieved by adding another electric motor in charge of the front-wheel drive. Considering the large range of battery energy levels the maximum power ranges from 285 kW to 586 kW, which is currently the most powerful version *P100D* with a maximum torque of 931 Nm, which allows acceleration from 0 to 100 km/h in just 2.4 seconds. The structure of the *Tesla Model S* is shown in Figure 2.16.

The drivetrain is a compact unit consisting of an electric motor, an inverter and a single-stage reduction gear with differential gear. The drive is obtained from a three-phase induction motor. The principle by which a copper cylinder starts to rotate around its axis when an electric current is passed through the electromagnetic casing inside which the cylinder is located, was discovered by Nikola Tesla. The inverter converts the DC current of the high-voltage battery into the alternating current used by the electric motor. The lithium-ion battery is located in the floor of the vehicle and consists of more than 7000 cylindrical cells that are interconnected in several modules. The mass of the 85 kWh battery is 544 kg, which is a quarter of the total mass of the vehicle.

LITERATURE

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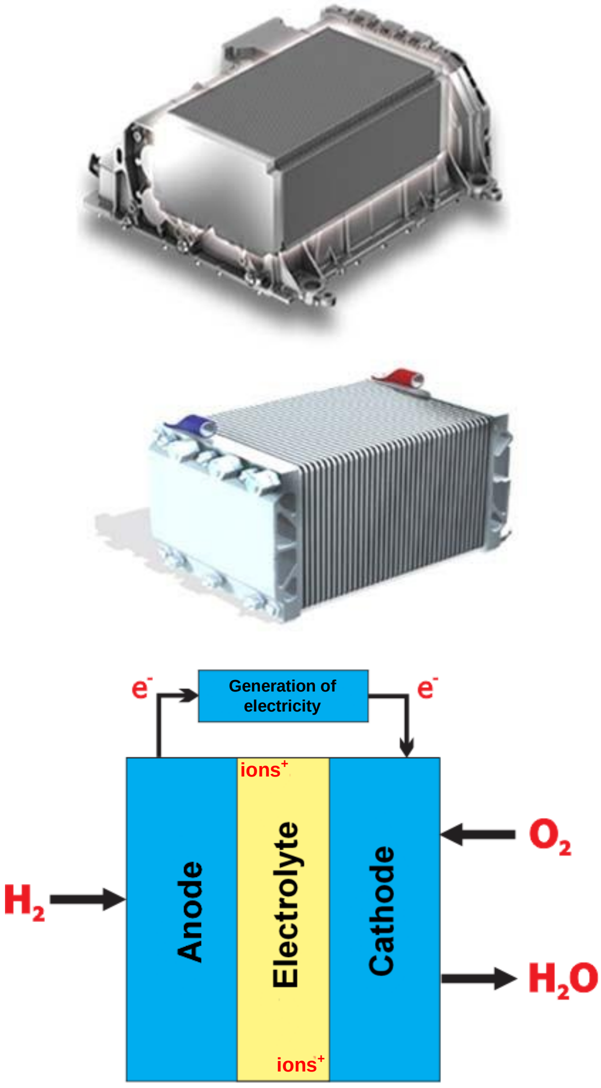
3. FUEL CELL ELECTRIC VEHICLE (FCEV)

Fuel Cell Electric Vehicle (FCEV) are electric vehicles running entirely on electricity, but it is primarily obtained through fuel cells that use hydrogen stored under high pressure in the tanks on the vehicle itself as fuel. During movement these vehicles have no exhaust emission.

3.1 FUEL CELLS

The technology that is increasingly attracting attention, and is most common in hydrogen-fueled cars, is fuel cell technology. A fuel cell converts chemical energy into electrical energy by means of a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent. It is important to distinguish fuel cells from batteries, because fuel cells need a flow of fuel and oxygen (air) in order to maintain a chemical reaction and produce electricity. The advantage of a fuel cell is the continuity in electricity production as long as it is supplied with fuel and oxygen (air).



3-1. Figure

(a)

Fuel cell

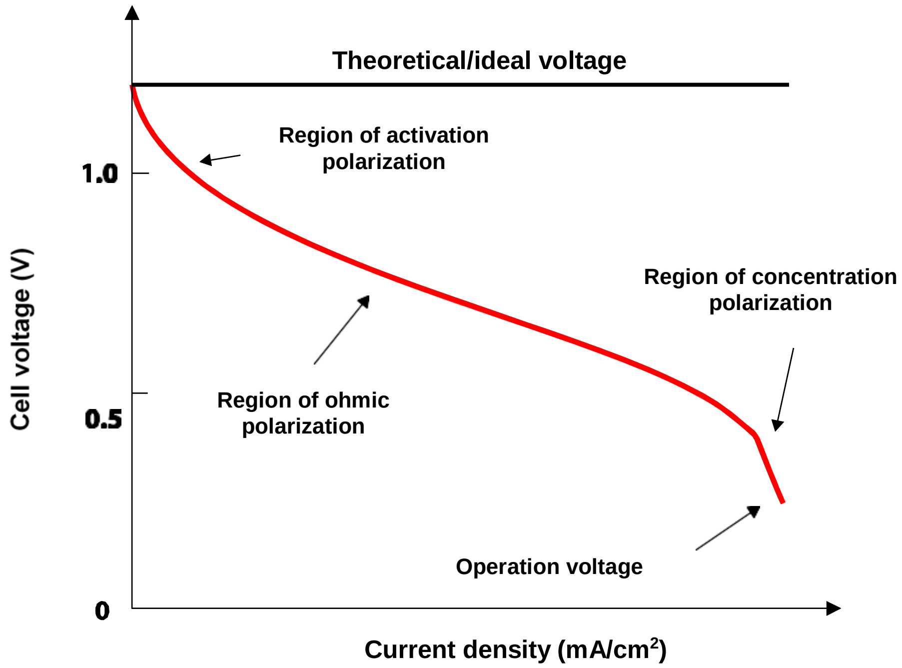
(b)

Fuel cell pack

(c)

Fuel cell operating principle

There are many types of fuel cells, but the principle of their operation is essentially the same. Each of them consists of a cathode and an anode and an electrolyte that allows positively charged hydrogen ions (or protons) to move within the fuel cell. The appearance of the fuel cell, as well as the operating principle is shown in Figure 3.1. The cathode and the anode contain a catalyst that causes the fuel to react to generate positively charged ions and electrons. As the hydrogen ions move through the electrolyte after the reaction, the electrons at the same time move from anode to cathode through the external circuit, producing a direct current. Fuel cells are classified mainly by the type of electrolyte used and by the reaction initiation time, which can vary from one second to several minutes. It is important to note that fuel cells individually produce a very small potential difference (only 0.7 V), and are therefore serially connected, thus providing a sufficiently large voltage that can meet certain requirements. In addition to electricity, fuel cells produce water and heat, even a small amount of nitrogen oxides and other emissions depending on the fuel used. The energy efficiency of fuel cells ranges from 40 to 60%, and can be increased by up to 80% if the cogeneration process is carried out, i.e. the released heat is used.



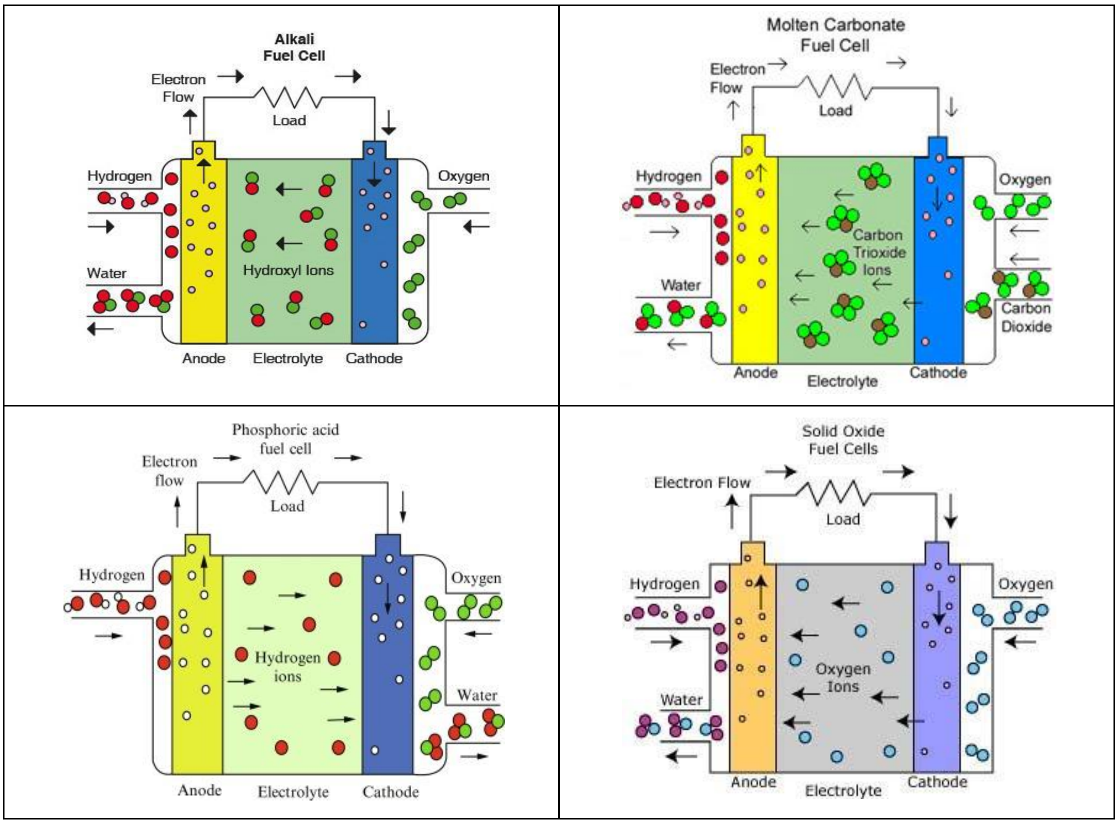
3-2. Figure
Chart of fuel cell voltage and current density

Several segments are taken into account when constructing a fuel cell. As has already been said, the type of electrolyte and its chemical composition determines the type of the fuel cell itself. The fuel it uses is also very important, and pure hydrogen is the most commonly used. The anode catalyst excites fuel and breaks it down into electrons and ions, and it's usually a fine powder made of platinum. The cathode catalyst is most often made of nickel and converts ions into chemical compounds such as water or less frequently dioxides of certain elements.

Under theoretical conditions, fuel cells would function without losses, however, this is not the case. During normal operation, the most significant losses occurring in the fuel cell are: activation losses, which are directly dependent on the degree of chemical reaction; ohmic losses (i.e. voltage drops) due to the resistance of the flow of ions and electrons through the medium; and concentration losses, depending on the concentration of reactants, i.e. its changes. As can be observed from the chart in Figure 3.2, the theoretical voltage achievable by a fuel cell is approx. 1.25 V, however, due to the energy efficiency of the cell of 40-60%, the actual operating voltage of the cell is between 0.6 and 0.7 V. Depending on the purpose of the fuel cell, they can be connected in two ways: in series (when higher voltages are obtained) or in parallel (when higher power is obtained). For the purposes of motor vehicles, fuel cells shall be arranged in a way that enables uniform distribution of reacting gases to each cell, in order to obtain maximum output power.

According to the type of electrolyte, five main types of fuel cells are distinguished: polymer electrolyte membrane fuel cells (*PEMFC*), alkaline fuel cells (*AFC*), phosphoric acid fuel cells (*PAFC*), molten carbonate fuel cells (*MCFC*) and solid oxides fuel cells (*SOFC*). Three of five types of fuel cells (*PEMFC, AFC* and *PAFC*) belong to the group of low-temperature fuel cells, while the remaining two types belong to the group of high-temperature fuel cells. These types of fuel cells are shown in Figure 3.3.

Fuel cells with a polymer membrane as electrolyte (*PEMFC*) are reduced to proton-exchange during the reaction. A polymer in the form of a very thin, permeable sheet is used as the electrolyte. The efficiency of these cells is between 40% and 50%, and the operating temperature is around 80°C, which gives them an exceptional advantage over other types of cells in vehicle applications. The disadvantage of these fuel cells is that the fuel they use must be in pure form, and platinum-based catalysts are used on both sides of the membrane, which increases the price of the fuel cell. Fuel cells with alkaline electrolyte, on the other hand, use potassium hydroxide in water as electrolyte, which leads to efficiency of 70% and operating temperature of 150 - 200°C. They produce a power of 300 W to 5 kW and require pure hydrogen, however, as in the previous example, platinum-based catalysts are too expensive. It's an interesting fact that these fuel cells were used in the famous Apollo spacecraft to produce electricity and drinking water. Fuel cells that use phosphoric acid as an electrolyte have an efficiency of between 40% and 80%, and their operating temperature is from 150 to 200°C. They can produce output up to 200 kW and tolerate carbon monoxide up to a concentration of 1.5%, which extends the choice of fuels that can be used for the reaction. Platinum-based catalysts are necessary, and all internal parts must withstand acid corrosion.



3-3. Figure
Fuel cell types by electrolyte type and their operational schemes

The remaining two types of fuel cells are high-temperature types because their operating temperatures are above 600°C, which is significantly higher than the already mentioned types of cells. Fuel cells with molten carbonate as electrolyte (*MCFC*) use high-temperature components of carbonate salts. Their efficiency is between 60% and 80%, and their operating temperature is around 650°C and they can produce an output of up to 2 MW. Nickel-based catalysts are significantly cheaper than the platinum used in other fuel cells, however, high temperature and carbonate electrolytes lead to corrosion of the anode and cathode and thus shortened life of the fuel cell. Another disadvantage is their slow initiation time due to the required temperature (650°C), which is the operating limit of these fuel cells. The main advantage is their resistance to impurities, so even carbon-rich fuels such as coal gas are compatible with this system.

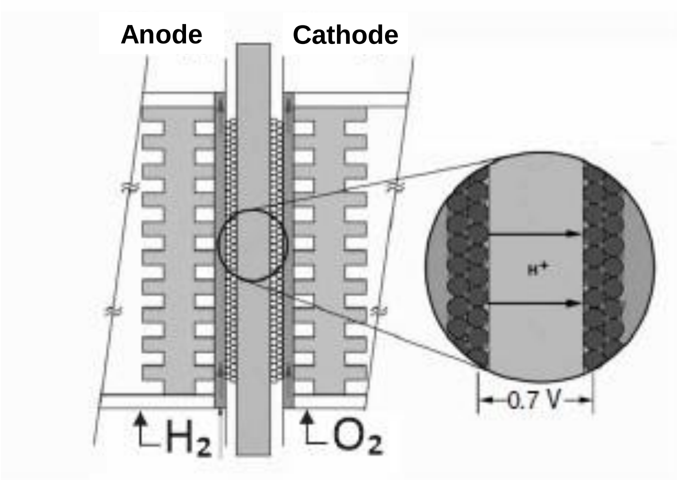
Fuel cells with solid oxides as electrolyte (SOFC) use ceramic components of metal oxides such as calcium and zirconium. Their operating temperature is between 800 and 1000°C, and they can use virtually all fuels, including natural gas. They can produce power of up to 100 kW and have efficiency of approx. 60%. As in the case of MCFC cells, high temperature is a disadvantage in terms of initiation time, and therefore there are more possibilities for using such cells for stationary setups, rather than mobile ones. A potential problem is also the carbon deposition that can occur on the anode, slowing down the internal reformation process in the cell. Although they can't leak, these cells could be ruptured.

3.1.1 CONSTRUCTION AND CHARACTERISTICS OF PEM FUEL CELLS

For the needs of hydrogen powered motor vehicles, *PEM* fuel cells are the optimal choice due to their low operating temperature, which enables mobility that is essential for vehicles.

As already stated, the *PEM* fuel cell consists of a proton-permeable membrane and two platinum electrodes between which the membrane is located. Teflon seals and collectors are also components that complete a single fuel cell. Different electrolyte materials were used for the needs of the proton membrane, and the thickness of the membrane itself is only a few tens of micrometers. The correct functioning of the membrane implies the exchange of hydrogen ions (protons), not electrons, as well as the prevention of gases (hydrogen, oxygen) from penetrating the opposite compartment of the fuel cell. Breaking down hydrogen molecules is relatively easy with the help of a platinum catalyst, however, the same is not the case with oxygen, where significant losses in electricity occur. This is why platinum is currently the best option for catalysts. It is also important to note that membranes are mostly made of synthetic polymer, while they are less often based on phosphoric acid, where operating temperatures of over 100°C can be reached.

In addition to the low operating temperature, compactness is what distinguishes these fuel cells when used in motor vehicles. The amount of water or steam, as a reaction product, is also important, so attention must be paid to this as well: too much water will flood the membrane, while too little water will dry it out; in both cases this will lead to a drop in output power. In addition to the water problem, the problem can be the membrane itself that is intolerant to carbon monoxide (its concentration must not be higher than 1 mg/m^3), and is sensitive to metal ions that can occur due to corrosion of metal bipolar plates, metal components in the fuel cell or some contaminant from fuel or oxidant.



3-4. Figure
PEM fuel cell cross-section

Output power	**1-500,000**
Operating temperature	50-100°C (Nafion) 120-200°C (*PBI*)
Cell efficiency	50-70%
System efficiency	30-50%
Power density	0.1-1.5 kW/kg
Pressure in the cell	1-5 bar
Advantages	Higher power and current density, longer lifespan
Deficiencies	Carbon monoxide intolerance, problem of drainage of water and precious materials as a catalyst

3-1. Table
Individual characteristics of PEM fuel cells

As can be seen in Figure 3.4, the single cell consists of both graphite plates and Teflon masks. Teflon masks serve as gaskets, which retain the gas flow in the active zone, and represent excellent protection along the periphery of the membrane. Graphite plates are in fact current collectors and also retain the gas flow. When packing fuel cells, graphite plates retain the gas flow on both sides and are then considered bipolar plates. The gas diffusion layer must be electrically conductive, thin and porous, and its role is to connect the catalyst to the current collector. This layer should optimally be constructed from at least 30% of nafion, the material from which the fuel cell membrane itself is most often made.

As shown in Table 3.1, the success of *PEM* fuel cells in the automotive industry is reflected, despite some shortcomings, in the long life and higher current and power densities compared to other fuel cells, as well as in the relatively low operating temperature. It is also important to say that these fuel cells are extremely compact and light, so their packaging does not increase the mass of the vehicle too much.

Although the theoretical efficiency of *PEM* fuel cells is approx. 83%, the actual efficiency is usually only slightly higher than 50%.

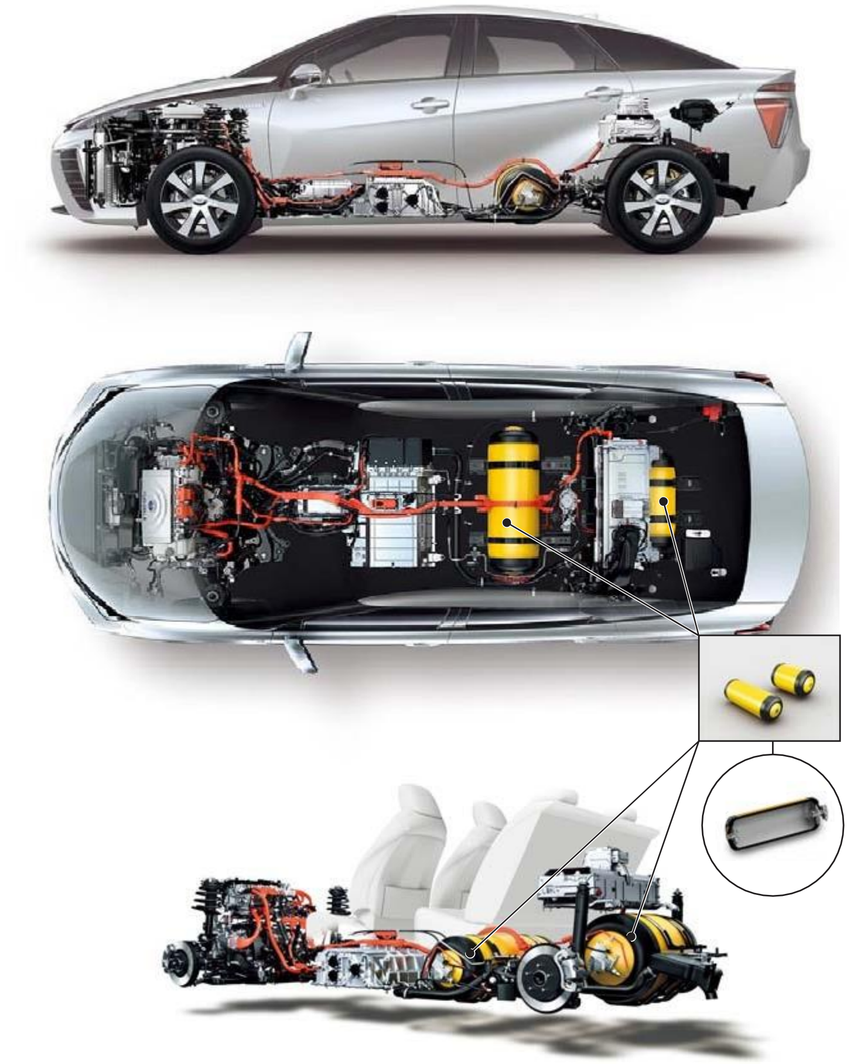
3.2 EXAMPLES OF FUEL CELL VEHICLES

Many manufacturers try to introduce future customers to this technology and provide them with all the necessary information on various hydrogen-powered car concepts. It is therefore not surprising that almost every renowned manufacturer today has at least one concept of a hydrogen vehicle, which is particularly dominated by Japanese manufacturers. At this point, it seems that *Toyota* leads the way, having presented the first model of a hydrogen-, i.e. fuel cells, powered car, at the end of 2014, which was commercialized. It is a *Mirai* model (Figure 3.5). As in the case of other manufacturers, everything started from the concept (*Toyota FCV concept*), and the name of the model is interesting, because *Mirai* translated from Japanese means the future.

Toyota Mirai uses PEM fuel cells, 370 cells in the pack, lined up in series. One fuel cell is only 1.34 mm wide and weighs 102 g, while the total weight of all cells in the assembly is 56 kg. The unladen weight of the vehicle is 1850 kg. Increasing the voltage enables the dimensions of the electric motor to be reduced, as well as the number of fuel cells in the package.

The vehicle accelerates from 0 to 100 km/h in 9.1 seconds. The refilling of the hydrogen tank, which can be seen in Figure 4.9, takes 3-5 minutes and with a full tank the car can travel almost 500 km. By the way, there are two tanks in this car that are made of carbon fiber reinforced plastic and together weigh 88 kg. Fuel cells, arranged in a three-dimensional grid structure for easier dispersion of air (oxygen), can develop a maximum output of 114 kW, i.e. 153 hp. The electric motor delivers power of 113 kW (152 hp) and torque of 335 Nm. This car also has a 245 V rechargeable nickel metal hydride battery.

Of course, *Toyota* is not the only manufacturer to embark on the challenge of hydrogen-powered cars. *Honda Clarity* (Figure 3.6) inherited its concept model and started selling back in 2008. *Clarity* uses fuel cells that develop a power of 100 kW, as much as an electric motor with a torque of 256 Nm. The hydrogen tank has a capacity of about 4 kg and with a full one can travel 372 km. The voltage of the lithium ion battery is 288 V.

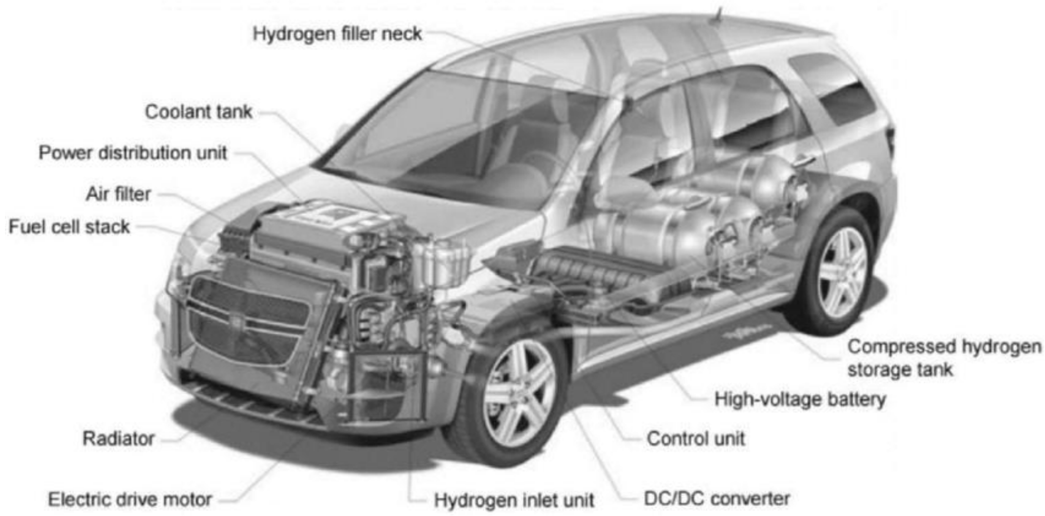


3-5. Figure

Overview of individual components and position of the hydrogen tank on the Toyota Mirai 2015

General Motors was also developing hydrogen-powered cars. The last one presented to the public was *HydroGen4* (Figure 3.7), in 2007 and during the period it was produced (2008-2010), about a hundred cars left the factory. The *HydroGen4* is based on the *Chevrolet Equinox*, and has fuel cells that provide a maximum power of 93 kW. The hybrid drive system has a 35 kW nickel-metal-hydride battery and a synchronous motor with torque of 320 Nm. The maximum speed this car could achieve was 160 km/h, and it reached speed of 100 km/h in 12 seconds. The hydrogen tank was type IV with a maximum amount of 4.2 kg and a projected range of 320 km.

3-6. Figure
Honda Clarity



3-7. Figure
HydroGen4 hydrogen-powered vehicle

Hyundai began series production of cars using fuel cells with its *ix35* model. The latest model of this generation from 2012 can achieve a speed of 160 km/h, and it accelerates from 0 to 100 km/h in 12.5 seconds. The power produced by the fuel cells is 100 kW and the battery is 24 kW. The hydrogen tank is of type IV and can hold 5.6 kg of hydrogen, while with a single charge the vehicle can travel a projected length of 588 km.

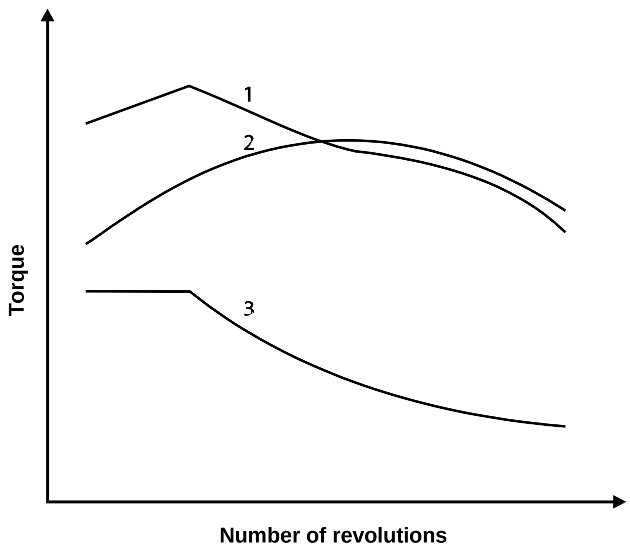
It is clear that future solutions must overcome many more obstacles that stand in the way of commercialization. Experts predict that, although we already witness certain models in offer, mass production of these vehicles will not come to life in the next 15-20 years.

4. HYBRID ELECTRIC VEHICLES (HEV), PLUG-IN HYBRID ELECTRIC VEHICLES (PHEV)

Every vehicle in which two or more different types of energy are converted into mechanical energy that drives is called a hybrid vehicle. Hybrid electric vehicles, which use an internal combustion engine (petrol or diesel) and an electric motor for propulsion, are the most widespread. To a much lesser extent, a combination of the IC engine and hydraulic or pneumatic drive system is also used, as well as some other variants that will not be discussed. The hybrid vehicle combines the good sides of both drive sources, and reduce the number of weak points to a minimum.

Considering the power it releases, the IC engine has a small weight and occupies a relatively small space, refueling the tanks is fast and with enviable autonomy of movement. However, IC engines cannot boast a high efficiency, and their exhaust emission cannot be ignored. Also, the field of use of the IC engine in real conditions is not the area of minimum specific fuel consumption (lower number of revolutions with high load), while the form of the torque curve indicates the fact that it is not available to a greater extent at low number of revolutions of the engine, i.e. when the vehicle starts moving, which is of particular importance in urban conditions.

Unlike the IC engine, the maximum torque of the electric motor is available immediately, which is of great importance when the vehicle starts moving. In addition, the electric motor does not have an exhaust emission of harmful gases, whereby a high efficiency does not depend on the load. On the other hand, for the same output power, electric motors weigh more than IC engines, and additional space in a vehicle must be provided for batteries, which also contributes to the increase in weight. The process of recharging the batteries is considerably slower compared to recharging the tank with fossil fuel. The vehicle autonomy is quite limited compared to IC engine-driven vehicles. Figure 5.1 shows the torque curves of the different drivetrains.



4-1. Figure
Torque curves for different types of drivetrain;

1 – hybrid drive

2 – IC engines

3 – electric motor

Taking into account the stated strengths and weaknesses of the electric motor and the IC engine, as well as the available torques at different rpm, it can be concluded that combining these two motors achieves the following advantages:

- The IC engine should be used exclusively in the field of higher energy efficiency, i.e. lower specific fuel consumption;
- Lower displacement engines may be used;
- When braking, part of the kinetic energy can be converted into electrical energy by means of an electric motor which then operates in generator mode;

More efficient operation of the IC engine achieves lower exhaust emissions, while in some cases the drive is enabled only by the electric motor when the exhaust emissions are absent.

4.1 HISTORY

Although the hybrid vehicle was patented at the end of the 19th century, its real development began at the end of the 20th century due to pollution, as well as due to the rise in oil prices and the limitation of its reserves.

The first hybrid vehicle was presented at the Paris Motor Show in 1899. The vehicle was manufactured by the French company *Vendovelli & Priestly* in cooperation with the Belgian company *Anciens Etablissements Pieper* as a tricycle. The two wheels on the rear axle were driven by independent electric motors, while the internal combustion engine with a maximum power of ¾ hp was paired with a 1,1 kW generator. The role of the generator was to recharge the batteries and thus increase the vehicle autonomy. Belgian Camille Jenatzy presented a hybrid vehicle with a parallel structure at the Paris Motor Show in 1903. This vehicle featured combination of an internal combustion engine with a maximum power of six horsepower and an electric motor with a power of fourteen horsepower. Frenchman Louis Antoine Kriéger built a serial hybrid in 1902. He used two independent electric motors to drive the wheels on the front axle. The motors were powered by electricity from 44 lead cells submerged in acid, supplemented by a 4.5-horsepower engine that used alcohol as a fuel.

The *Lohner-Porsche* petrol-electric car called *the Lohner-Porsche Mixte Hybrid* (Figure 4.2) used an internal combustion engine to drive the generator that was used to charge the battery pack. These batteries were charged by electric motors located in the front wheel assembly. A classic transmission system was not necessary. Due to its simplicity, the transmission was executed without mechanical losses, with then incredible degree of utility of 83%. When it first appeared at the world exhibition in Paris, on April 14, 1900, the *Lohner-Porsche* with an electric motor delighted the automotive world. With three hundred of these vehicles manufactured, the patent was sold to Emil Jelinek. In 1905, Henry Piper patented a hybrid electric vehicle. His idea was to use an electric motor in addition to the IC engine in order to provide better acceleration with additional torque, so that the vehicle could accelerate to 40 km/h, instead of the usual 30 km/h, in 10 seconds. Three and a half years later, the internal combustion engines became powerful enough to achieve the aforementioned performance without the help of electric motors.

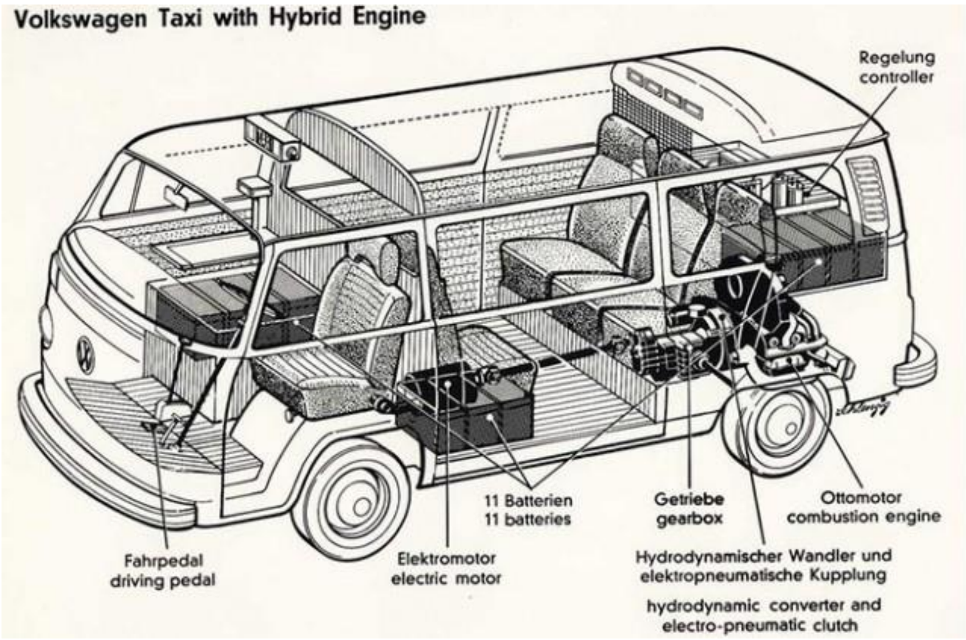
4-2. Figure
Vehicle Lohner-Porsche Mixte Hybrid

Low oil prices and cheaper production of IC engines gradually halted the development of hybrid vehicles. The exception is the *Owen Magnetic Model 60 Touring* from 1921 (Figure 4.3), where the internal combustion engine was used to drive the generator of electricity used by the electric motors mounted separately on each rear drive wheel.

The revival of the idea of electric vehicles, and therefore hybrid vehicles, began in the 1970s as an echo of the oil crisis in the United States, Britain, France, Germany, Italy and Japan. In 1976, the USA adopted an act on research of electric and hybrid vehicles. From the 1970s to the 1990s, the automotive industry developed experimental models of M and N category hybrid vehicles.

In the 1970s, the German manufacturer *Volkswagen* developed a hybrid vehicle called *VW Taxi* (Figure 4.4) as a modified model of the existing *VW T2* vehicle. A parallel hybrid configuration was used on this vehicle.

4-3. Figure
Owen Magnetic Model 60 Touring from 1921



4-4. Figure
VW Taxi

In 1980, *FIAT* introduced the *131 Ibrido*, an experimental prototype with a 903 cm^3 IC engine with a maximum power of 25 kW and a 24 kW electric motor. Regenerative braking system was also applied on the vehicle, and batteries weighing 175 kg were located in the rear of the vehicle. In the same year, the American company *Briggs and Stratton*, known for the production of internal combustion engines used in lawn mowers, developed a hybrid vehicle (Figure 4-5.). The vehicle was powered by a two-cylinder four-stroke IC engine with a maximum power of 16 hp combined with a 26 hp electric motor. That same year, the concept of the hybrid vehicle was also introduced by *Daihatsu*, and six years later *Twike* and *Gaselle* vehicles were developed.

4-5. Figure
Briggs and Stratton Hybrid Concept

In 1989, *Audi* introduced the experimental hybrid car *Audi Duo* based on the existing vehicle *Audi 100 Avant Quattro*. In addition to the internal combustion engine, the vehicle was also powered by an electric motor with a power of 12.6 kW. The electric motor provided power to rear driving axle and the IC engine powered the front drive shaft. The electricity that powered the electric motor was stored in a nickel-cadmium battery. The second generation of *Audi* hybrid vehicles was introduced in 1997, making *Audi* the first European manufacturer of hybrid vehicles. The vehicle under the same name, the *Audi Duo*, was a modified *A4 Avant*. The internal combustion engine and the electric motor powered the front drive shaft, and the electric energy storage battery was located in the rear of the vehicle. Since it had no success on the market, this model was soon withdrawn from production.

In 1997, the first generation of *Toyota Prius* was presented in Japan as the first hybrid vehicle to enter series production (Figure 4.6). In the first year of production, more than 18000 vehicles were sold.

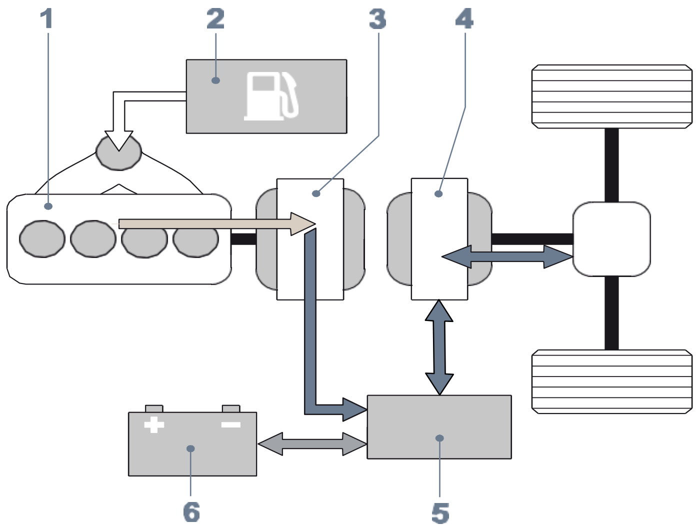
4-6. Figure
First generation Toyota Prius

4.2 HYBRID DRIVE STRUCTURE

The IC engine, the electric motor, the transmission system and the functional connection between them form an appropriate hybrid structure that enables different forms of energy transformation and energy flows, as well as the drive itself. Depending on the structure, the hybrid drivetrain can feature: a series configuration, a parallel configuration, a series-parallel configuration and a configuration with a planetary gearset.

4.2.1 SERIES CONFIGURATION OF THE HYBRID DRIVE

In hybrids with a series configuration, there is no mechanical connection between the IC engine and the mover. The drive is realized only by an electric motor, which can be powered by energy from batteries, or by energy obtained from a generator powered by an IC engine. The electric motor can provide the propulsion of the mover, but it can also produce electricity by regenerative braking, which is stored in batteries. So, the energy can be extracted from the batteries, but it can also be returned to them. Regenerative braking is realized by the electric motor resisting the movement of the movers, thus slowing them down. The energy of the mover rotates the rotor of the electric motor, which assumes the role of a generator, and thus produces electricity. In other words, instead of converting kinetic energy into heat, part of it accumulates into electrical energy. The series configuration of the hybrid drive is shown in Figure 4.7.



4-7. Figure
Series configuration

1 – IC engine

2 – tank

3 – generator

4 – electric motor

5 – pulse controlled inverter

6 - battery

The power flow (operation of the IC engine and electric motor) is managed by the control unit via the braking system command and the rpm controller command. In other words, the control unit determines the mode of vehicle movement. The operating modes can be as follows:

- Motion using the electricity from the battery, while the IC engine is switched off.
- Motion using the electricity obtained only from the generator driven by the IC engine. Battery energy is not spent on movement, nor is it recharged.
- Motion using the electricity obtained both by the operation of the IC engine (and generator) and from the battery.
- Simultaneous movement and recharging the battery using the electricity obtained from the generator driven by the IC engine.
- Regenerative braking, whereby the electric motor takes on the role of a generator and converts kinetic energy into electrical energy to recharge the battery, while the IC engine is switched off.
- Recharging the battery, whereby the energy of the IC engine is not used to start the electric motor, but only to recharge the battery.
- Hybrid battery recharging by regenerative braking by an electric motor, as well as by operation of the IC engine which drives the generator.

Series configuration of the hybrid drive has a number of advantages. Since there is no mechanical connection between the IC engine and the mover, engine operation can be optimized with the maximum possible efficiency, i.e. with the lowest possible consumption and exhaust emissions. This can be accomplished with an engine operating mode with a uniform number of revolutions and an appropriate load, i.e. a mode with the lowest specific fuel consumption. Since there is no mechanical connection with the driven movers, there is the possibility of installing high-speed motors such as gas turbines. For the same reason, the IC engine and the generator can be placed anywhere on the vehicle. Since the IC engine is not a direct driver of the vehicle, it is possible to use smaller displacement and therefore lower weight engines, which also leads to an additional reduction in exhaust emissions. The torque characteristic of electric motors does not require multi-stage and complicated transmission, which also contributes to the lower weight of the vehicle. In said configuration, it is possible to use two or more smaller electric motors, for each drive wheel individually, so that there is no need for a differential gearbox. Series configuration of the hybrid is simpler compared to other configurations.

Series hybrids perform well in urban driving conditions, with a large number of start/stop situations. With full batteries, in these cases, the vehicle is driven only by using the energy from the batteries. Low-speed movement in urban driving conditions can also be performed in purely electric mode. Considering that it leads to the lowest fuel consumption when the vehicle starts to move, the savings in terms of consumption and exhaust emissions for these vehicles are high.

Some solutions provide the possibility of supplying power to the battery from the mains (e.g. during the night), which further reduces fuel consumption.

However, the series configuration of the hybrid drive has its downsides, primarily referring to the multiple transformation of energy and the consequential losses. The energy obtained from the IC engine, where the first transformation from chemical or thermal to mechanical energy was carried out, is transformed twice more on the way to the drive movers. In the generator, first the mechanical energy is transformed into electrical energy and then the electrical energy is again transformed into mechanical energy at the output from the electrical motor, wherein losses are not negligible. Therefore, the efficiency of the generator and electric motor is very important. Series hybrids require batteries with a higher capacity compared to parallel hybrids, which significantly increases the weight. The existence of a generator also increases the weight of the vehicle and the price.

Series hybrids have poor performance when moving at high speeds (e.g. on highway) or on longer uphill stretches, because in those cases the used mode of movement uses electricity obtained exclusively from the generator powered by the IC engine, which is not good due to the mentioned transformation of energy and consequential losses.

Series hybrid configuration can be found in passenger vehicles, but more often it is used in heavy freight vehicles and buses, primarily due to the larger available space, but also batteries and generators of large dimensions and weight. It is also widely used in diesel-electric locomotives.

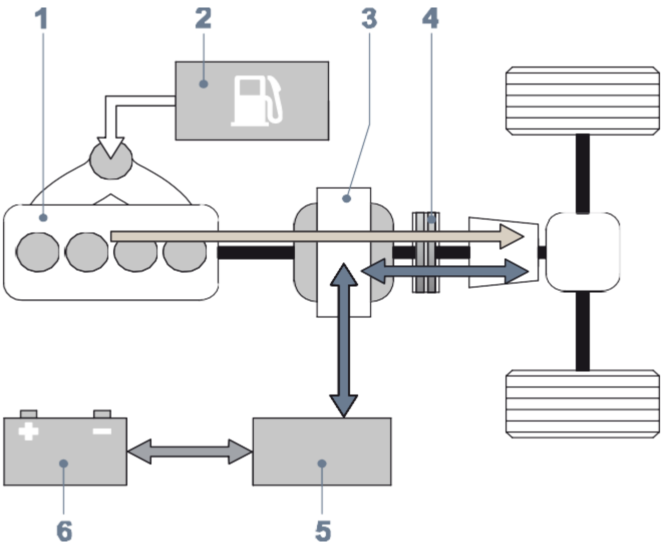
4.2.2 PARALLEL HYBRID DRIVE CONFIGURATION

The basic difference between the series and parallel configuration of the hybrid drive is that in the parallel configuration, the drive is realized directly, without energy transformation, using the energy of both the IC engine and the electric motor. Both engines are mechanically connected to the drive movers. In most conceptions, the primary source of power is the IC engine, while the electric motor provides assistance in certain driving modes. Therefore, propulsion can be provided solely by the IC engine or by the power of both the engine and the motor, although there are concepts that enable propulsion even only by the electric motor. The electric motor can take on the role of a generator in regenerative braking. If, when operating in optimal mode, the IC engine delivers excess power compared to the power required to overcome resistance (in the case of medium-intensity driving modes), this excess is used to recharge the battery. The operating modes are the same as for the series hybrid, with the addition of a mode in which the IC engine and the electric motor together participate in moving the drive wheels when the vehicle starts moving.

The power distribution gear set can be executed as classic (with fixed axes) or planetary reduction gearset, chain or transmission belts. Depending on the number of couplings, the type of power distribution elements, as well as the number of drive shafts, there are several different variants of parallel hybrid drive configurations.

A variant of the parallel configuration with one coupling (and one shaft) is shown in Figure 4.8. The electric motor is directly connected to the internal combustion engine. Unlike the series configuration, the IC engine rpm cannot be adjusted independently of the electric motor rpm. When decelerating the vehicle, the IC engine cannot be separated from the electric motor, which negatively affects the regenerative braking effect.

The drive mode of the electric motor is not possible in this variant, so its role is to assist the IC engine in movement or acceleration.



4-8. Figure Parallel single-coupling configuration

1 – IC engine

2 – tank

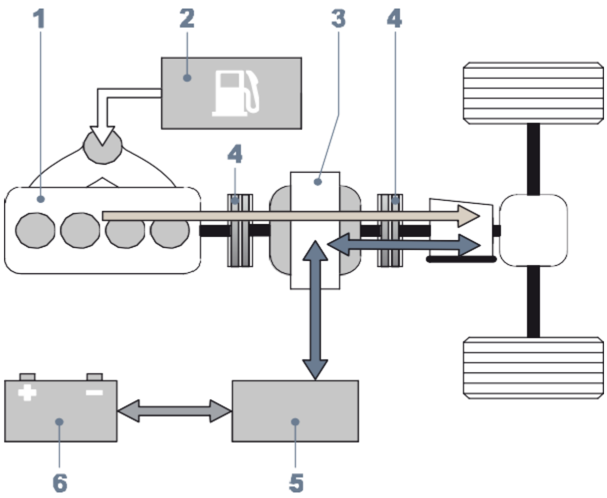
3 – electric motor/generator

4 – clutch

5 – pulse controlled inverter

6 - battery

Figure 4.9 shows a variant of a parallel configuration with two couplings (and one shaft). Progress has been made by adding another coupling between the IC engine and the electric motor, allowing the IC engine to be turned on and off as needed, i.e. to enable drive only from the electric motor. The IC engine can also be turned off when decelerating, which increases the regenerative braking potential. In order to achieve a smaller length of the entire assembly, there is a double coupling solution (Figure 4.10), i.e. two independent shafts, one of which is intended for the IC engine and the other for the electric motor.



4-9. Figure
Parallel configuration with two couplings

1 – IC engine

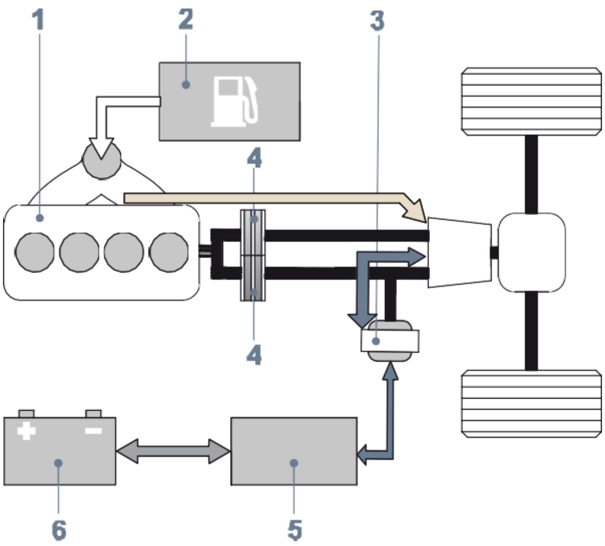
2 – tank

3 – electric motor/generator

4 – clutch

5 – pulse controlled inverter

6 - battery



4-10. Figure
Parallel configuration with two couplings and two shafts

1 – IC engine

2 – tank

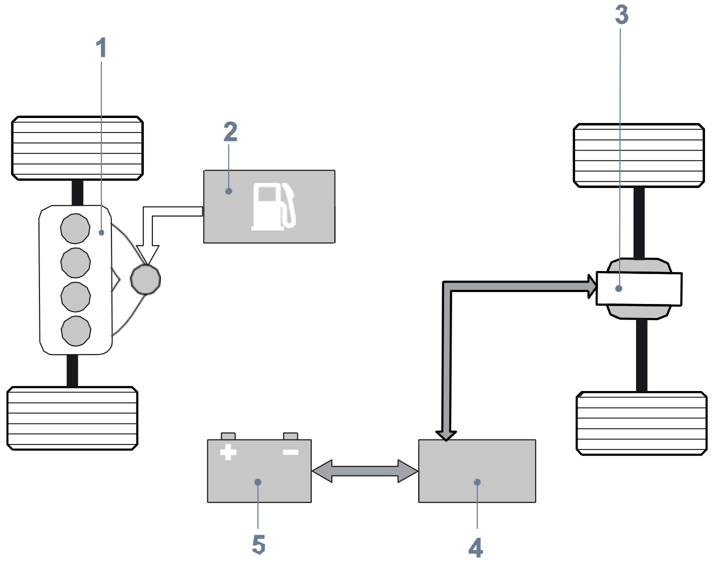
3 – electric motor/generator

4 – clutch

5 – pulse controlled inverter

6 - battery

Another parallel configuration of the hybrid drive shown in Figure 4.11 should be mentioned, which is the one that allows one drive shaft to be driven by an IC engine and the other by an electric motor. This configuration is classified as parallel because the powers of the IC engine and electric motor add up. In addition to all-wheel drive, torque distribution per wheel in wide range is also possible. In order to ensure permanent all-wheel drive, another generator powered by the existing IC engine is necessary. Thus, apart from regenerative braking, the batteries can be additionally recharged.



4-11. Figure
Parallel configuration with two drive shafts from different drive

1 – IC engine

2 – tank

3 – electric motor/generator

4 – pulse controlled inverter

5 - battery

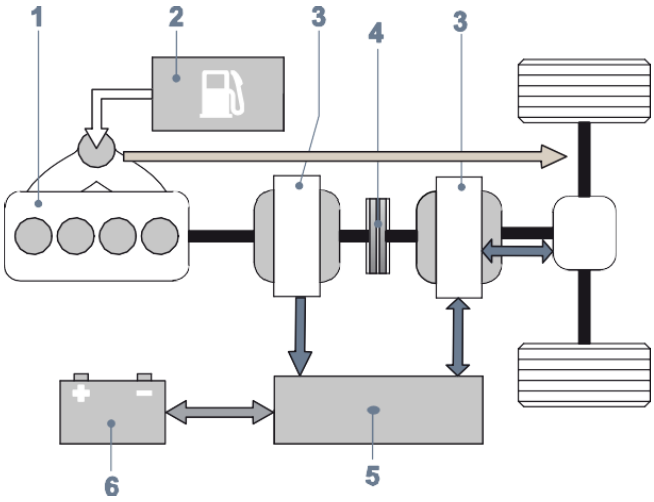
The good sides of the parallel conception of hybrid drive are reflected in the drive realized at the expense of both engine and motor, without energy transformation, i.e. with lower losses than with series one. The construction is more compact than in series configuration, if there is no generator, and due to the fact that the electric motor is of smaller dimensions. Therefore, this configuration also finds application in smaller vehicles.

The parallel drive configuration of a hybrid vehicle is relatively simple to achieve by upgrading the drive structure of an existing conventional vehicle. An electric motor and a battery are added to the IC engine, making the vehicle hybrid.

The main disadvantage of this concept is the fact that the IC engine and the electric motor are mechanically connected to the transmission so the operation of the IC engine cannot be ideally optimized. The above solution requires complex management of the hybrid system and complex power transmission systems.

4.2.3 SERIES-PARALLEL HYBRID DRIVE CONFIGURATION

The series hybrid was extended into a series-parallel hybrid (Figure 4.12) by establishing a mechanical connection through a coupling between two electric motors, one of which only has the role of a generator. A series-parallel hybrid can use the advantages of a series hybrid at low speeds of movement, and avoid disadvantages at higher speeds when the coupling is engaged and when the series-parallel hybrid behaves as a parallel hybrid. Since dual energy transformation is limited to the range of lower speeds and outputs, series-parallel hybrids require smaller electric motors than those in serial hybrids. The series-parallel configuration compared to the series configuration is not so compact, while compared to the parallel configuration it also requires an additional generator.



4-12. Figure Series-parallel configuration

1 – IC engine

2 – tank

3 – electric motor/generator

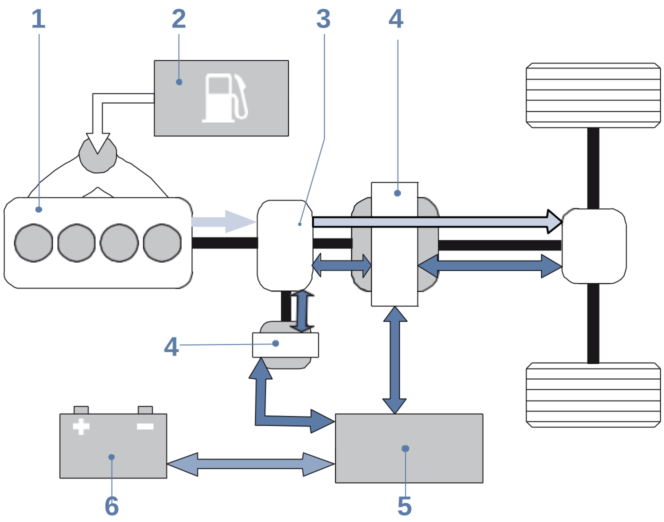
4 – clutch

5 – pulse controlled inverter

6 - battery

4.2.4 HYBRID DRIVE CONFIGURATION WITH PLANETARY GEARSET

The configuration with the planetary gearset combines the characteristics of parallel and series hybrids, i.e. it is most similar to the series-parallel configuration and in some sources these two configurations are considered the same. Part of the IC engine power is converted into electricity by means of a generator, and the rest, together with the power produced by the electric motor, is spent on the vehicle drive.



4-13. Figure Configuration with planetary set

1 – IC engine

2 – tank

3 – planetary gearset

4 – electric motor/generator

5 – pulse controlled inverter

6 - battery

The configuration with the planetary gearset is always a complete hybrid (see Table 4.1), because all the necessary functions are possible (start/stop function, regenerative braking, hybrid driving and entirely electric driving).

The structure is presented in Figure 4.13. The planetary gearset connects the IC engine, generator and electric motor via its three elements (sun gear, satellite carrier and external gear). With this in mind, the IC engine speed can be adjusted within certain optimal limits, regardless of the vehicle speed.

Part of the IC engine power is transmitted by means of a planetary gearbox mechanically to the drive wheels. The remainder of the power is transmitted electrically through double energy conversion to the drive wheels. Similar to a series hybrid, full electric transmission can be used in case of low power requirements. However, no arbitrary switching between mechanical and electrical drive is possible. In this way, the hybrid with a planetary gearset can achieve significant fuel savings at low and medium speeds. Additional fuel savings cannot be achieved at high speeds of movement.

The following characteristics are the strengths of this configuration: the operation of the IC engine is controlled so as to enable its most optimal performance under the given conditions; the IC engine can simultaneously drive the wheels and perform battery recharge; the vehicle can achieve exceptional accelerations with the help of both engines; in urban conditions the vehicle can be operated as a series hybrid with minimal air pollution, i.e. as a fully electric vehicle without air pollution; a significant reduction in fuel consumption and exhaust emissions in the most critical modes of urban driving.

The complex kinematics of the transmission mechanism (gearset), a large number of components and therefore a big weight, as well as a very complex control algorithm are some negative characteristics of this configuration.

4.3 DIVISION OF HYBRID VEHICLES IN RELATION TO THEIR FUNCTIONS AND DRIVING MODES (HYBRIDIZATION LEVELS)

In addition to the division related to the hybrid drive structure, which is described in subchapter 4.2, another division of hybrid vehicles is important, according to the level (degree) of hybridization, i.e. the functions that the hybrid electric vehicle can perform. Possible functions and driving modes are:

The START/STOP FUNCTION has the task of turning off the IC engine when the vehicle is not moving (road stop, waiting for the green light, etc.). The electric motor starts turning the crankshaft (starting) of the IC engine with the optimal speed. The engine start is instantaneous. The power source of an electric motor is a battery that can be charged by regenerative braking or by means of an electric motor that then operates as a generator driven by an IC engine. The electric motor may also supply power to some consumers in the vehicle while the IC engine is turned off.

REGENERATIVE BRAKING MODE – regenerative braking converts part of the kinetic energy into electricity when the vehicle is decelerating, which is performed by electric motor switched to generator operating mode driven by the wheels of the vehicle. The classic (hydraulic) braking system is still present to provide the required deceleration performance, but the energy converted to heat and lost in this case is less.

HYBRID MOTION MODE – In hybrid mode, the IC engine and the electric motor jointly provide the necessary torque for movement. It should be emphasized that in this mode, part of the IC engine torque, except for propulsion, can also be used to start the generator and produce electricity supplied by the electric motor, i.e. to charge the battery.

MOVEMENT USING THE ELECTRICITY ONLY (ELECTRIC MODE) – In this driving mode, the vehicle moves exclusively using the electric drive, that is, only with the torque produced by the electric motor by drawing energy from the battery. The IC engine then does not participate in the movement, i.e. there is no exhaust emission of harmful gases, while the noise level is also reduced.

FUNCTION OF BATTERY RECHARGE AT CHARGING POINTS – Some hybrid vehicles have the ability to connect to the power grid via an appropriate connection to recharge the battery. Such vehicles are designated as *plug-in hybrid electric vehicles - PHEV*).

The characteristic movement modes will be detailed schematically and described on the example of a *Toyota Prius* hybrid electric vehicle in subchapter 4.4.

Depending on the functions and modes supported by the hybrid electric vehicle, Table 4.1 gives their division according to the level of hybridization.

		Hybridization levels		
Functions/modes	*Micro hybrid*	*Mild hybrid*	*Full hybrid*	*Plug-in hybrid*
Start / stop	●	●	●	●
Regenerative braking	●	●	●	●
Hybrid mode		●	●	●
Electric mode			●	●
Recharging at charging points				●

4-1. Table
Hybridization levels according to functions/modes supported

In accordance with the already described cycle according to which fuel consumption tests are carried out (*Modified New European Driving Cycle – MNEDC*), certain results on fuel savings have also been obtained. Thus, a micro hybrid can save between 4% and 5% of fuel, a mild hybrid between 10% and 15%, while a complete hybrid can save between 20% and 30% of fuel. It is logical that the greatest fuel savings are achieved with the plug-in hybrid and it is between 50% and 70%, whereby the electricity consumed was not considered.

4.4 EXAMPLES OF HYBRID ELECTRIC VEHICLES

4.4.1 TOYOTA PRIUS

Toyota Prius is the most widespread hybrid electric vehicle, because since 1997, when the production of the first generation of this vehicle began, over six million vehicles of different generations and body shapes have been produced until 2016. Since the start of series production, a total of four generations of *Toyota Prius* have been presented (Figure 4.14).

4-14. Figure
Four generations of Toyota Prius – Generation I (1997-2003), Generation II (2003-2009), Generation III (2009-2015) and Generation IV (2015-)

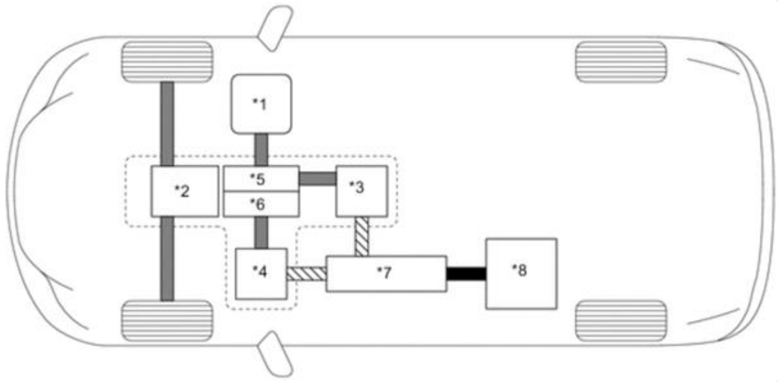
Toyota has developed a special *Hybrid Synergy Drive (HSD)* system that has been perfected through generations and is an example of a complete hybrid with a planetary gearset.

4.4.1.1 HYBRID SYSTEM COMPONENTS

Figure 4.15 shows the basic components of the *Toyota Prius* hybrid system of the fourth generation, as follows:

*1 – IC engine;
*2 – main and differential gear;
*3 – generator;
*4 – electric motor;
*5 – planetary gearset;
*6 – electric motor speed reduction gear;
*7 – inverter;
*8 – high-voltage battery.

The 1798 cm^3 petrol engine, with a maximum power of 71 kW at 5200 rpm and a maximum torque of 142 Nm at 3600 rpm, operates according to the Atkinson cycle, which, thanks to the delayed closing of the intake valves, enables greater efficiency than the engine operating on the Otto cycle. The generator is designed as an electric motor with a permanent magnet with a maximum voltage of 600 V. The drive electric motor, also with a permanent magnet and the same maximum voltage as the generator, has a maximum power of 53 kW and a maximum torque of 163 Nm. Both electric motors are water-cooled. The inverter has the role of enabling the direct current of the high-voltage battery to be converted into alternating current for starting the electric motor and generator (when starting the IC engine), as well as to increase the nominal battery output voltage from 201.6 V to 600 V of the maximum voltage that can be used by electric motors. Also, the transformation of direct current from battery to alternating current is also necessary for other electric consumers in the vehicle, such as, for example, air conditioning. The high-voltage nickel-metal-hydride (NiMH) battery is compactly located under the rear seat and is air-cooled.



4-15. Figure
Hybrid system components in Toyota Prius of fourth generation with types of interconnections:

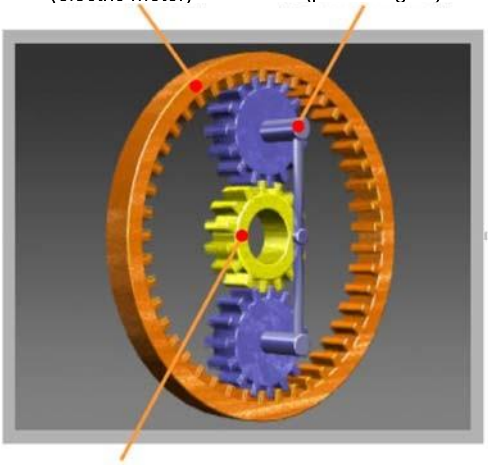
- direct current electrical connection

- mechanical connection

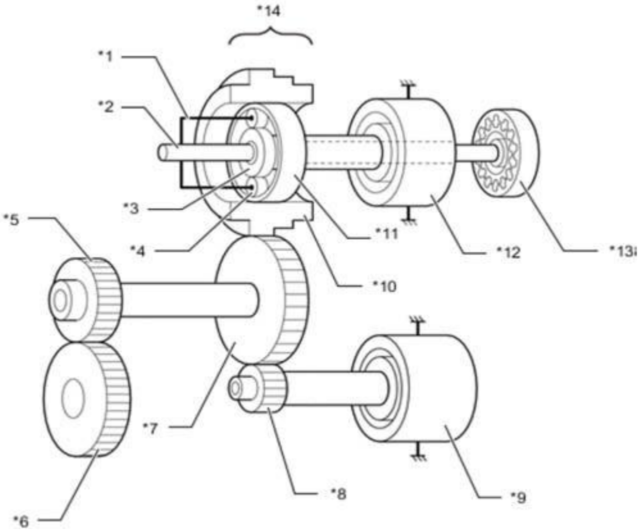
- alternating current electrical connection

The power distribution gearset is a particularly interesting assembly which, with the help of a determined algorithm, enables the distribution of power between the IC engine, generator, electric motor and drive wheels. Figure 4.17 shows a cross-section of the assembly consisting of the IC engine, generator, electric motor and drive distributor in the form of a planetary gearset for the second generation of the *Toyota Prius.*

In the solution shown (Figure 4.18), the sun gear is connected to the generator, the planet carrier with the IC engine, while the external gear (ring) is connected to the electric motor. From the external gear (ring), the torque is transmitted to the drive wheels via a chain, an additional reduction gear, a main gear and a differential gear. The solution shown enables the IC engine to drive the generator for the production of electricity and, at the same time, to deliver a torque intended for the drive that can be increased by that of the electric motor (hybrid driving mode), whereby all the elements of the planetary gearbox are rotated. Also, it allows driving mode which uses only the electric motor (electricity) – the ring is rotated while the sun gear and the satellite carrier are stationary. When charging the battery, while the vehicle is not in motion, the ring is stationary while the planet carrier rotates the sun gear, which drives the generator to produce electricity. Frequent starting of the IC engine due to start/stop function with the presented solution is very simple; the generator, which can get electricity from the high-voltage battery, switches to the electric motor mode in order to start the satellite carrier, i.e. the IC engine, via the sun gear.



4-18. Figure
Hybrid drive planetary gearset in Toyota Prius of the second generation

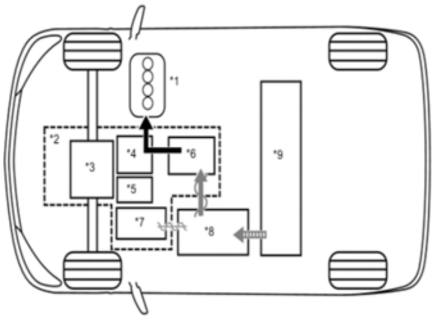
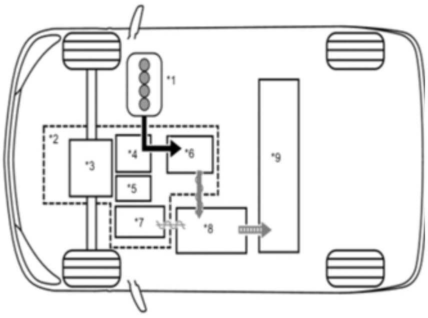
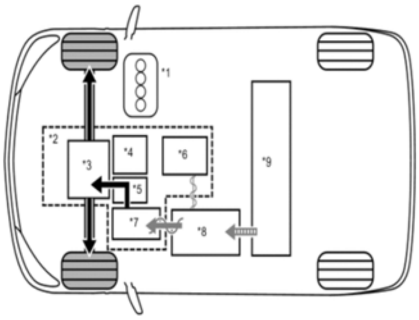
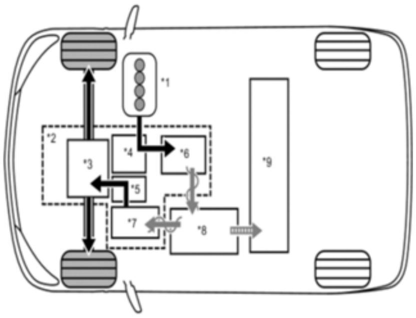
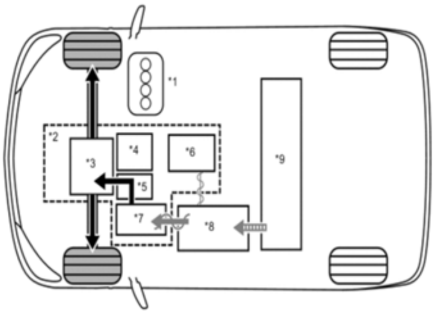
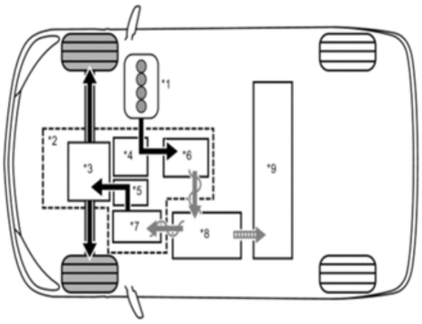
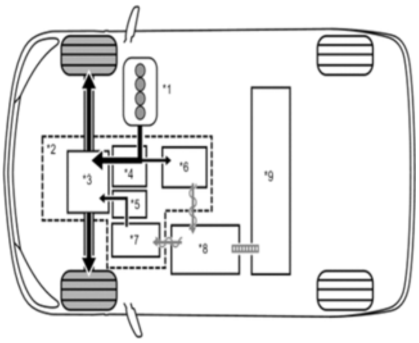
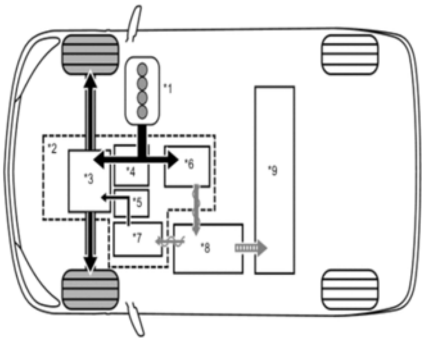


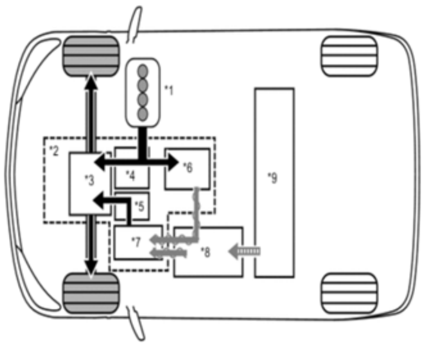
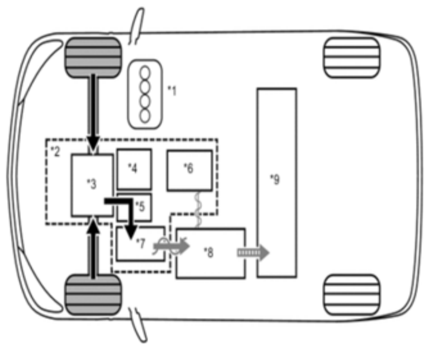
4-19. Figure
Hybrid drive gearset in Toyota Prius of the fourth generation

4.4.1.2 CHARACTERISTIC MODES

The operation strategy determines how the drive power is divided between the IC engine and the electric motor. It decides to what extent fuel-saving and emission-reducing potentials are used. The operation strategy determines the operation of the hybrid system in different modes, as well as the implementation of functions such as start/stop and regenerative braking, all based on a number of influential parameters such as, for example, speed of movement and acceleration/deceleration of the vehicle, engine load, battery charge. In accordance with the above, there are several characteristic driving modes that determine the operation of the components of the hybrid drive and the energy flow between them and they are presented in Table 4.2 together with the corresponding schematic representation of the hybrid system.

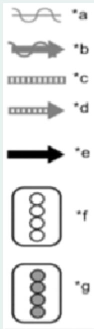
Using electricity from the battery, the generator can also operate as an electric motor when powered via a planetary gearset by an IC engine (the generator is powered by a sun gear driven by a satellite carrier connected to the crankshaft of the engine). Charging the battery while the vehicle is stationary is accomplished by means of a generator, which is powered by the IC engine via a planetary gearset. Therefore, the IC engine might switch on while in stationary mode, only to recharge the battery, not for propulsion, as expected.

	
Starting the IC engine	*Charging the battery when the vehicle is not moving*
	
Start of movement	*Start of movement with min. battery level*
	
Movement with low resistance - lower constant speed of movement (entirely on electric drive)	*Movement with low resistance - Lower constant speed of movement with minimum level of battery*
	
Movement with constant speed - cruising	*Movement with constant speed – cruising with min. level of battery*

	
Max acceleration	*Deceleration*

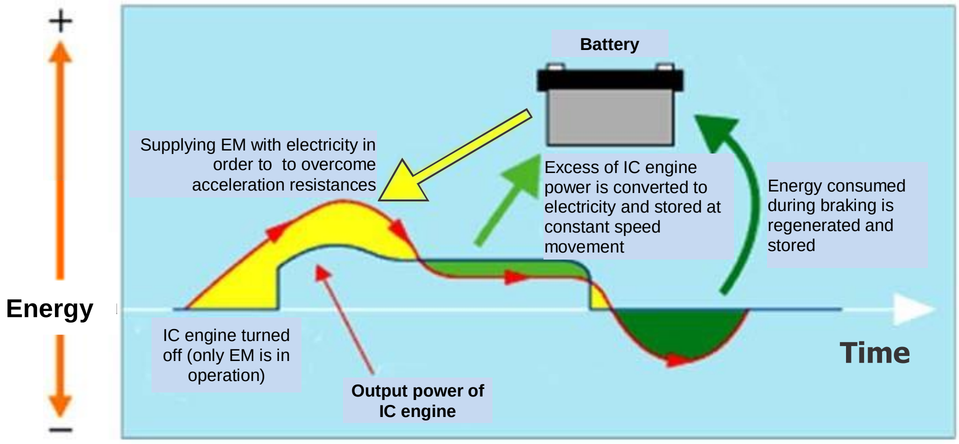
4-2. Table
Characteristic modes

**1 – IC engine*
**3 – main and differential gear*
**4 – planetary gearset*
**5 – electric velocity electric motor*
**6 – generator*
**7 – electric motor*
**8 – inverter*
**9 – high-voltage battery*



**a – alternating current*
**b – flow alternating current*
**c – direct current (201.6 V)*
**d – flow of direct current*
**e – flow of mech. energy*
**f – IC engine not running*
**g – IC engine running*

As already mentioned, the electric motor has a better torque characteristic than the IC engine to start the vehicle from the standstill condition, so that is the responsibility of the electric motor that receives electrical energy from the battery, and if it is not sufficiently charged, the IC engine that drives the generator is switched on, and the generated electrical energy is used to operate the electric motor and recharge the battery. The same principle is used when moving at lower uniform speeds, i.e. with low resistances, whereby movement only with the help of electricity can be realized if the battery is charged to the adequate level. The cruise mode implies that the IC engine and the electric motor participate in the operation of the vehicle, whereby the required electrical energy for its drive is obtained directly from the generator powered by the IC engine via a planetary gearset. So part of the IC engine's energy is used to propel the vehicle, and part to propel the generator. If the battery level is critical, it is increased by additional generation of electricity from the generator. The maximum acceleration mode implies that the electric motor, in addition to the electrical energy produced by the generator, also uses the one from the battery in order to improve the acceleration performance. In the regenerative braking process, the electric motor switches to the generator operating mode driven by the drive wheels and thus produces electrical energy that recharges the batteries.



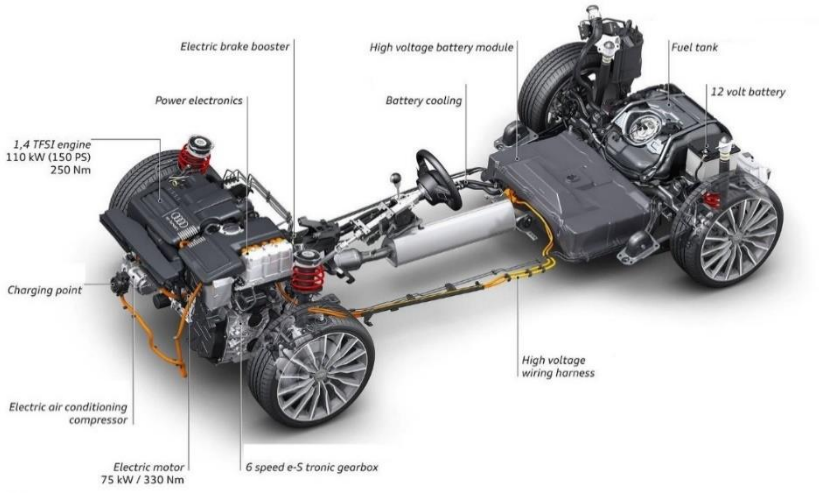
4-20. Figure
Schematic representation of the energy balance in characteristic modes ov movement

The energy balance of the various modes is shown schematically in Figure 4.20.

With a carbon dioxide emission of 70 g/km and an average annual distance travelled of 20,000 km, the 4th generation *Toyota Prius* annually saves more than one tonne of CO_2 compared to the vehicle of the *D* segment with a modern diesel engine.

4.4.2 VW GOLF GTE/AUDI A3 SPORTBACK E-TRON

The *VW* Group implemented the idea of reduced fuel consumption and exhaust emissions through a hybrid electric drive in its *VW GOLF GTE / AUDI A3 Sportback e-tron* models, whereby it wanted to keep the sporty touch of these vehicles. Figure 4.21 shows the concept of the subject hybrid drive.



4-21. Figure
VW hybrid drive concept applied on the vehicle AUDI A3 Sportback e-tron

A parallel configuration of the *plug-in* hybrid drive consisting of a petrol engine (displacement of 1.4 liters and power of 110 kW) and an electric motor with an output of 75 kW, was applied. An electric motor is a synchronous motor with permanent magnets on the rotor, whose rotational speed is the same as the rotational speed of the stator's magnetic field. Since it is a three-phase electric motor, an inverter is necessary to convert a high voltage direct current, using 6 high-power transistors, into a three-phase current. The electric motor is located between the coupling that engages/disengages the IC engine to/from the drive and the gearbox with double multi-layer coupling and six transmission stages (Figure 4.22). In this way, in certain modes, where it is more favorable, the operation of only the electric motor, that is, only the IC engine, is enabled, or their joint operation when the total power may reach 150 kW.

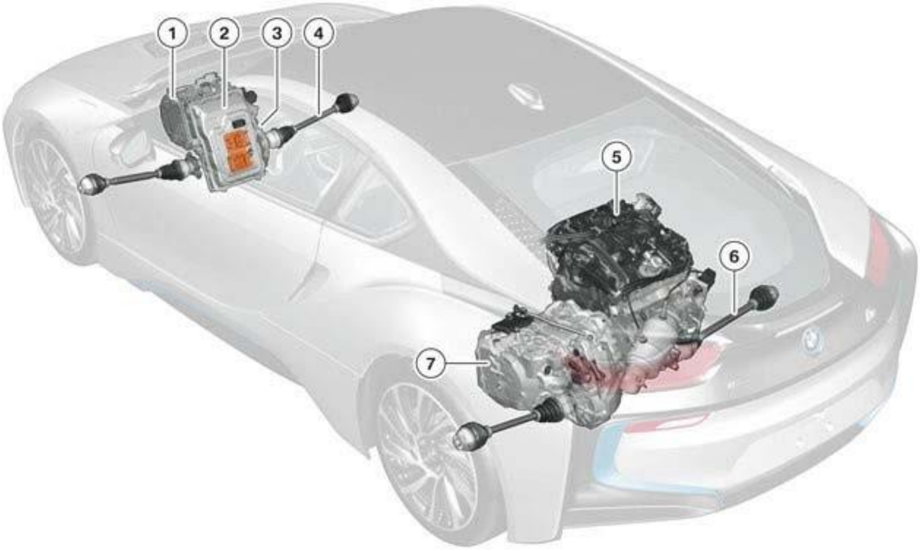
The high-voltage battery used in this hybrid vehicle is lithium-ion, with a capacity of 8.8 kWh and a weight of 120 kg. There are two possibilities of charging the battery using the IC engine and connecting it to the electricity grid (*plug-in*). When connected to the grid, charging lasts 3.5 hours, but with the help of a special device, the charging power is increased from 2.3 to 3.6 kW, and the charging time is reduced by one hour. Also, the battery is supplied with electricity through regenerative braking, using the kinetic energy of the vehicle and the operation of the electric motor as a generator.

4-22. Figure
Transmission system in AUDI A3 Sportback e-tron

Such a structure provides an autonomy of 939 km, i.e. 50 km by using only the electricity, and according to the *NEDC* test for hybrid vehicles, the emission of carbon dioxide is 35 g/km, which corresponds to a consumption of only 1.5 liters per 100 kilometers, but also 11.4 kWh of electricity per 100 km. The feasibility of sport characteristics, with very low consumption and exhaust emission, is also evidenced by the fact that it takes 7.6 seconds to achieve a speed of 100 km/h, while the maximum speed is 222 km/h.

4.4.2 BMW i8

As already pointed out in item 4.2.2, there are multiple solutions for the parallel configuration of the hybrid drive. One of them is a solution with two drive shafts, one driven by an electric motor and the other by an IC engine. A real example is the high-performance sports vehicle *BMW i8*, which has both drive shafts, with the front driven by an electric motor and the rear by an IC engine. Figure 4.23 shows a schematic representation of the components of both drivetrains, while Figure 4.24 shows a cross-section of the vehicle.



4-23. Figure
Schematic view of the front and rear drivetrains in BMW i8

1 – electric motor

2 – control unit of the electric motor

3 – two-stage gearbox

4 – axial shaft of the front axle

5 – IC engine

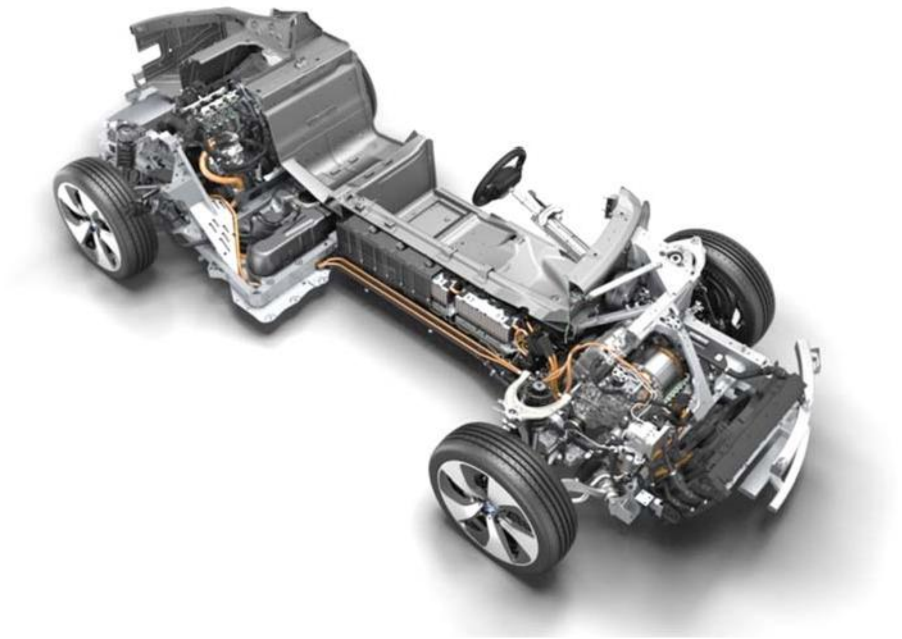
6 – axial shaft of the rear axle

7 – six-stage automatic transmission

The three-cylinder petrol engine (displacement of 1499 cm^3, maximum power of 170 kW at 5800 rpm, maximum torque of 320 Nm at 3700 rpm and CO_2 emissions of 49 g/km) drives the rear wheels via a six-stage automatic transmission. A generator used for recharging the high-voltage battery when necessary, is attached to the IC engine, but also serves as the starter of the IC engine at the expense of electricity from the battery. On the other hand, the electric motor drives the front wheels via a two-stage gearbox. The electric motor has a weight of 49.5 kg, a maximum power of 96 kW for a maximum of 5 s, i.e. a continuous power of 25 kW, a torque of 250 Nm in the range from 0 to 4000 rpm, and a maximum speed of 11400 rpm. Its characteristics at full battery supply are shown by diagrams in Figure 4.25. There are several options through which the driver can influence the agility, i.e. the economy of the vehicle, which define the operation strategies for control of the entire drivetrain (*Comfort, Eco Pro, Sport, Max eDrive*).

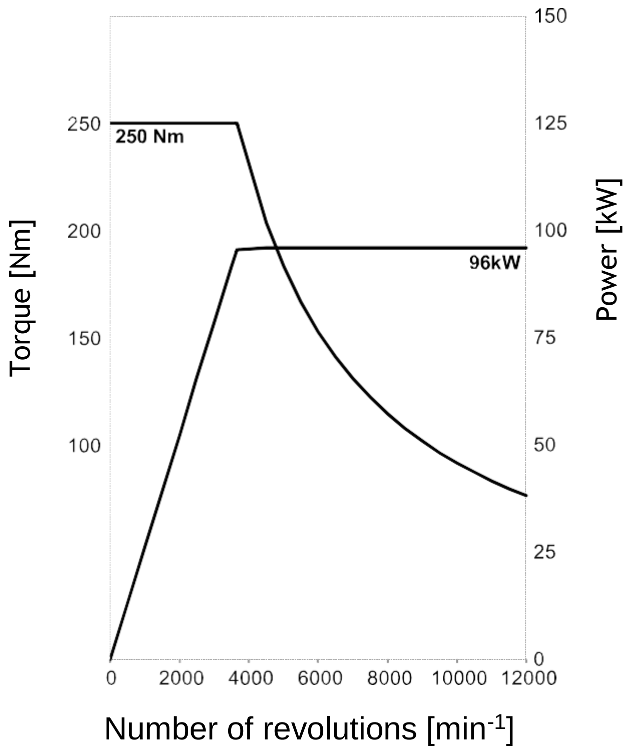
One stage of transmission in said two-stage gearbox is used for *Comfort, Eco Pro* and *Sport* options, while the other stage is used when the vehicle is moving using only the electric drive

(*Max eDrive*), and the shift is automatically performed when selecting said drive option (strategy). Then you can go about 37 km if speed is not over 120 km/h.



4-24. Figure
Cross-section of the BMW i8

It is interesting to note that by entering the planned destination in the system for satellite navigation of the vehicle's trajectory, the computer can plan a strategy of maximum energy efficiency, taking into account the uphill and downhill inclinations (to obtain regenerative energy) on the intended trajectory, as well as moving through populated places (at lower speeds only using the electric drive, without exhaust emission and with low intensity noise) and outside populated places (where, depending on the resistance, desired performance and battery charge, the IC engine is switched on).



4-25. Figure
Characteristics of torque and power of electric motors

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5. ELECTRIFICATION OF EXISTING VEHICLES WITH IC ENGINES

Electrification of vehicles that use only an internal combustion engine is carried out by installing electric motors, batteries, inverters with other necessary devices, as well as reduction gears if necessary, after the construction of a complete engine, a gearbox, an exhaust system and a tank with fuel supply hoses. There are also solutions where the electric motor is paired with a manual or automatic transmission of a conventional vehicle, but this is less common.

Electrification of vehicles using an internal combustion engine is a significant alternative to new electric vehicles which can accelerate the transition from conventional vehicles to fully electric vehicles in a relatively short time and with a significant reduction in costs in relation to the development and production of new electric vehicles. The first association with the electrification process is often the restoration and electrification of vehicles of historical importance, while today there is an increase in interest in the electrification of modern motor vehicles. This significantly contributes to the promotion of environmental-friendly modes of transport, while at the same time electric vehicles become more accessible to potential customers.

Governments of several countries around the world have recognized electrification of existing vehicles as a positive practice and approved this type of vehicle modification through appropriate laws. Electrification itself is a more economical and sustainable solution compared to the production of new electric vehicles because, in a way, in enables the re-use of existing vehicles and provides a significant contribution to the electrification of the entire fleet, while significantly reducing exhaust emissions. Vehicles modified in this way generally have less autonomy compared to newly produced electric vehicles, but are, above all, a more financially advantageous solution. The electrification process is gaining more and more popularity, as recognized by many states subsidizing the conversion of a conventional vehicle into an electric vehicle.

Also, the number of companies dealing with this type of modification is constantly growing and mostly deal with modifications of smaller city vehicles, which are among the more affordable and popular on the market. There are also several companies involved in the electrification of buses with diesel engines.

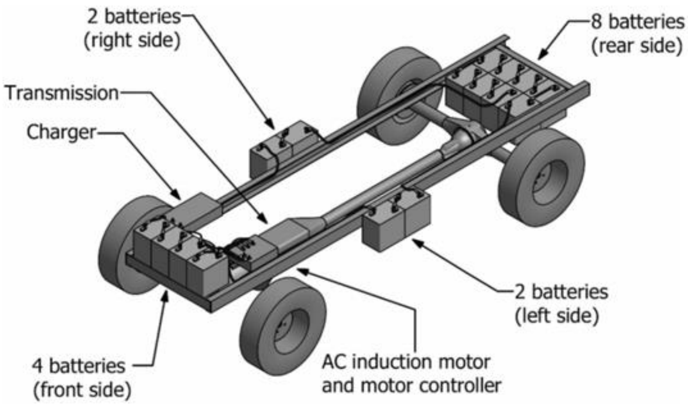
When there is no requirement for greater autonomy of vehicles, batteries are generally placed in the luggage compartment and/or engine compartment, while otherwise batteries are most often installed from the underside of the vehicle floor. The installation of batteries on the underside of the vehicle floor often leads to the need to increase the distance of the vehicle from the ground (vehicle clearance), which, with the increase in weight, can negatively affect the dynamics of vehicle movement, so this should be taken into account. It is important to note that the weight of the batteries has the greatest impact on the weight of the electrified vehicle (the weight of the batteries can be over 450 kg).

In certain cases, it is necessary to make appropriate modifications to the supporting system and/or the suspension system in order to make the dynamic behaviour of the electrified vehicle as close as possible to that of the conventional vehicle undergoing modification.

Figure 5.1 shows the components necessary for electrification of one vehicle.

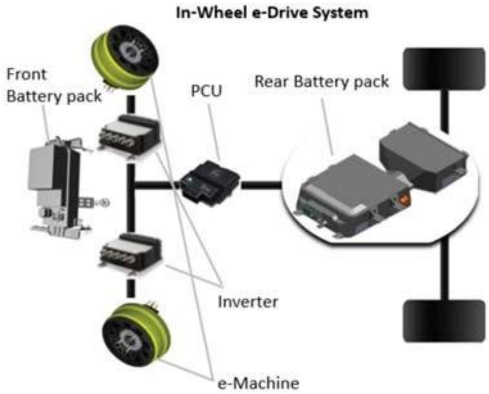
5-1. Figure
Components necessary for vehicle electrification

Figure 5.2 shows one of the ways of installing batteries, electric motors and controllers on the chassis of an off-road vehicle manufactured with a petrol engine. Batteries are installed on the front and rear end, as well as on the sides of the supporting system (chassis). The asynchronous induction motor is positioned in the front of the vehicle, while the transmission that was present in the vehicle before electrification is retained.

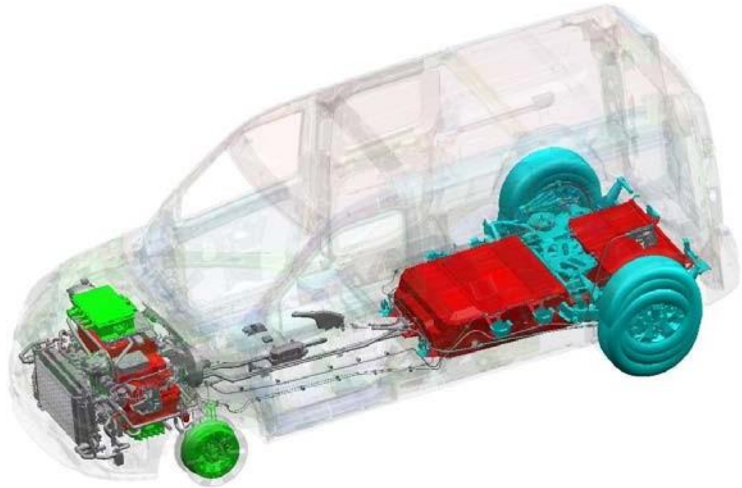


5-2. Figure
Position of the electric drive components in the electrified off-road vehicle

A schematic view of a vehicle electrified by installing an electric motor in the front wheels of a light goods vehicle is shown in Figure 5.3. Batteries are installed at the front (under the hood) and rear end (in front and behind the rear axle) of the vehicle. The position of the electric drive components (electric motors and batteries) on the vehicle is shown in Figure 5.4.

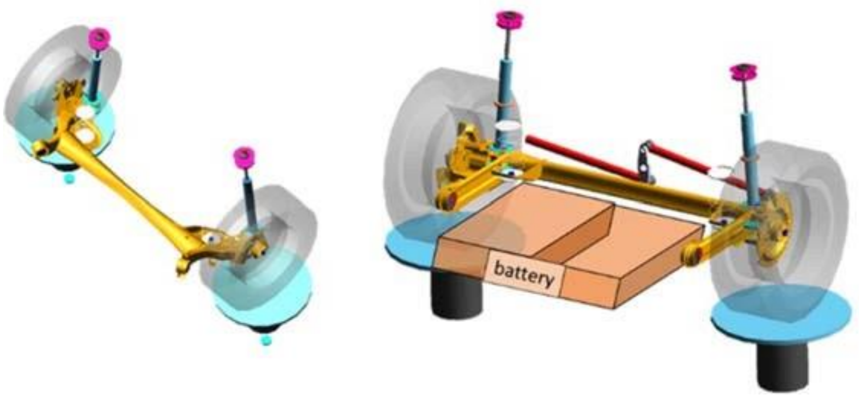


5-3. Figure
Electric drive components of an electrified vehicle with electric motors in wheels



5-4. Figure
Position of electric drive components in electrified vehicle with electric motors in wheels
(batteries – red; electric motor, inverter and controller – green)

Figure 5.5 shows the structure of the torsion axle before (Figure 5.5 – left) and after electrification of the vehicle (Figure 5.5 – right). The changes were made to allow the battery to be placed on the underside of the vehicle floor. Such modifications may lead to an extension of the time necessary for electrification of the vehicle.



5-5. Figure
Modification of the torsion axle structure in order to place the battery on the underside of the vehicle floor

5.1 GUIDELINES FOR ELECTRIFICATION OF EXISTING VEHICLES WITH INTERNAL COMBUSTION ENGINES

Below will be given the guidelines defined by the *Technology Committee - Association for Promotion of Electric Vehicles* established in Japan, concerning the electrification of vehicles with internal combustion engines.

The guidelines define the electrification of passenger and light goods vehicles that can also be equipped with manual or automatic transmissions, while solutions are also allowed in which the elements of the power transmission system are completely removed from the vehicle. Also, some of the guidelines can be used when electrifying other types of vehicles.

So, the requirements have been defined in relation with, among other things:

- protection against electric shock caused by high voltage circuits, including protection against direct and indirect contact with electrical conductors;
- installation of batteries;
- various on-board devices, such as vehicle mode indicators, electric motor controllers, etc.

The insulation color of high-voltage electrical conductors (except those located in a closed enclosure) shall be orange. DC conductors must be coated in red on positive and in black on negative power lines. Also, different lines of high-voltage conductors can be marked in the same way, but only at the ends of the insulation, which must be orange.

The protection against electric shock in the event of an accident must be executed in such a way that the appropriate mechanisms (usually inertial switches) switch off high voltage power circuits. Thus, a high-voltage circuit breaker must exist on the vehicle to enable it to be switched off without the use of tools, in order to protect people during the servicing of the vehicle, for example. If this is solved in another way, it must be ensured that the battery case cannot be opened in case of switched on power supply of the high-voltage lines, while the reactivation of the high-voltage lines must be disabled as long as the battery case is open.

Electrical devices, in particular those used for controlling and managing the operation of electric motors, must be approved with regard to electromagnetic compatibility with the environment in which they operate (appropriate documentation shall be provided by the device manufacturer). These devices must not interfere with the operation of other devices on the vehicle, while at the same time they must be resistant to electromagnetic waves emitted by other devices and equipped with appropriate sensors that allow monitoring the insulation resistance between live lines and grounding.

Great importance is also given to the safety of the batteries themselves and their installation. The technical requirements relating to batteries are based on the requirements defined in the UN Rulebook No. 100. This Rulebook defines different procedures for testing the battery, where its resistance to vibration, mechanical and thermal shocks, fire, etc. is checked.

Batteries must be equipped with a system that will stop charging when the battery is fully charged, to avoid overcharging.

When installing the battery, care should be taken to evenly distribute the weight of the vehicle along the axles so that the permissible axle loads defined by the manufacturer of the vehicle being converted to electrical are not exceeded.

For batteries with operating voltages over 60 V of direct current (DC) or 30 V of alternating current (AC) (effective value), the appropriate conditions regarding the installation location on the vehicle are defined, where, in case of installation of the battery in the front of the vehicle, it is necessary to place the battery so that the horizontal distance from the front edge of the vehicle to the battery itself (measured parallel to the longitudinal axis of the vehicle) must be at least 420 mm. In the case of installation of the battery in the rear of the vehicle, the horizontal distance from the rear edge of the vehicle to the battery (measured parallel to the longitudinal axis of the vehicle) must be at least 300 mm.

The guidelines define that the batteries of passenger vehicles with a maximum of 9 seats or freight vehicles with a maximum permissible weight of less than or equal to 3500 kg must be installed in such a way that at a longitudinal acceleration of ±196 m/s^2 it does not break or crack, while the same is defined for lateral accelerations of ±78.4 m/s^2.

The battery housing must be designed to allow easy maintenance and monitoring of the electrolyte level inside the battery (if applicable). Also, a battery level indicator must be installed in the vehicle in order for the driver to assess the remaining autonomy of the vehicle based on this information.

The connection between the electric motor and the transmission (if retained on the vehicle) must be made by means of a metal plate which must be of sufficient strength and produced with sufficient precision to allow the vehicle to move in all possible driving modes. The electric motor must be installed in such a way as to enable the operation without vibrations that could lead to the failure of one of the elements in the power transmission system.

The maximum engine torque shall be in the range that will allow the operation of the power transmission system with the designed load, especially if the electrification is carried out with keeping the transmission of the conventional vehicle modified. In this case, the installation of an electric motor whose maximum torque value is not greater than the maximum torque value of the internal combustion engine being removed from the vehicle is considered satisfactory.

If the maximum motor torque can be easily increased, for example by changing the setting of the electric motor controller, such changes must be prevented appropriately (by disabling free access to the electric motor controller).

The attachment of the electric motor to the vehicle supporting system without modifications of the brackets over which the internal combustion engine was attached is only allowed if the weight and maximum torque of the electric motor are not greater than the weight and maximum torque of the internal combustion engine originally installed on the vehicle.

Appropriate measures ensuring the water resistance of electric motor, electrical devices, lines and other electrical installations must be taken to protect these elements during driving in rain or snow, washing vehicle, etc.

Particular attention should be paid to the choice of electrical lines connecting the battery and the electric motor, in order to ensure that they are suitable for the transmission of the appropriate current intensity that the battery can supply to the electric motor.

In the case of electric motors installed in vehicle wheels, extra attention should be paid to the protection against external influences, because the operating conditions of electric motors installed in this way are difficult.

Also, the possibility of installing a specific electric motor in the vehicle must be checked through appropriate expressions:

- smaller vehicles: $MPW \times g \leq 122 \times P_{max} - 600$;
- larger vehicles: $MPW \times g \leq 135 \times P_{max} - 1500$,

where:

P_{max} - maximum power of the electric motor [kW];

MPW – maximum permissible weight [kg];

g – acceleration of the Earth's gravity [m/s^2].

Data on the electric motor, such as maximum power and maximum torque, may be supplied by the electric motor manufacturer or read from the manufacturer's rating plate attached to the electric motor, in case the motor manufacturer has installed a suitable plate.

Controllers of electric motors and similar devices must be protected against thermal radiation in order to prevent potential damage. In case of failure of the controller or similar devices during the use of the electrified vehicle (e.g. high temperature rise), the driver must be warned by the appropriate indicator on the control panel.

Unwanted accelerations or inability to decelerate the vehicle in case of failure of the controller or similar devices are not allowed. This is especially true in case of interruption of the transmission of signal from the “throttle” command to the controller or failure of the “throttle” position sensor. In the event of a failure detected by the electric motor controller, it must be possible to completely interrupt the electric motor power supply or the electric energy recovery while the movement of the vehicle by means of inertia and the use of brakes are enabled. The “throttle” command must have double return springs of sufficient stiffness, which should allow the command to return to its initial position when the driver stops acting on it.

A contactor is placed between the battery and the controller of the electric motor, which can fully withstand difficult operating conditions, such as frequent switching on and frequent change of the driver's action on the “throttle” command. The contactor must be selected so that it can operate with currents whose intensity is greater than the maximum current that can occur in the electric motor controller and high voltage protection devices, such as fuses.

Appropriate measures shall be taken to prevent the vehicle from starting when lights or other auxiliaries important for the safe movement of the vehicle cannot be switched on, but it shall also be prevented that these devices become unusable when the vehicle is prevented from moving due to a voltage drop in the battery or for any other reason. One way is to equip the vehicle with batteries specifically designed for auxiliaries that can be powered via a DC/DC converter. Batteries intended for supplying auxiliaries with energy can also be powered by solar cells.

The vehicle without battery for auxiliaries must have a DC/DC converter whose output current can withstand the maximum power consumption of the auxiliaries. Such a DC/DC converter should also provide power to the emergency lights (switching on all direction indicators simultaneously) when the vehicle is forced to stop due to a voltage drop in the battery used to power the vehicle.

The battery charger used to power the auxiliaries in the vehicle should be designed to stop charging when the battery used to power the vehicle is fully charged. Lithium battery chargers should be designed to automatically stop battery charging for auxiliaries to prevent battery cell overcharging.

The battery used to power the auxiliaries in the vehicle must not adversely affect the autonomy of the vehicle or the life of the battery used to power the vehicle and must comply with the specifications required by the manufacturers of battery used to power the vehicle.

When electrifying a vehicle equipped with a braking system that uses engine intake depression to provide braking assistance to the driver, the electrified vehicle must be equipped with an electric pump or similar device to provide assistance equivalent to that which existed prior to electrification.

The vehicle must have a driver warning system that indicates any failure of an electric pump or similar device that provides braking assistance to the driver, including loss of depression.

Regenerative braking should exist as an alternative to engine braking possible in conventional vehicles with internal combustion engines, while the use of regenerative braking must also be enabled when the battery is fully charged.

Also, 3 operation modes of brake lights are defined depending on the intensity of the achieved deceleration during regenerative braking:

- without the activation of brake lights for decelerations less than or equal to 0.7 m/s^2;
- brake lights can be switched on (optional) for decelerations between 0.7 m/s^2 and 1.3 m/s^2;
- brake lights shall be on when regenerative braking is activated if the vehicle deceleration is greater than 1.3 m/s^2.

The vehicle must have a system that visually alerts the driver of whether the vehicle is in *standby* mode or in driving-ready mode. Also, if the vehicle is in a driving-ready mode when the driver leaves the vehicle, an audible or visual warning for the driver must be activated.

Appropriate measures must be taken to prevent sudden starting of the vehicle and other undesirable situations. Thus, in electrified vehicles, there must be certain mechanisms that will replace equivalent mechanisms in, for example, conventional vehicles with manual transmission, where engine starting is disabled until the coupling command is fully pressed. In electrified vehicles where manual transmission systems have been retained, this can be solved by disabling the power supply to the electric motor as long as the “throttle” command is pressed. If the electrified vehicle has an automatic transmission, shifting the transmission to driving mode can be disabled if the brake command is not pressed.

When the reversing control device is in use, there must be an appropriate audible warning for the driver. If this function was not available on the vehicle before electrification, it should be implemented after the modification. Also, the vehicle speed when reversing must be adequately limited.

Changing the driving mode from forward and reverse in electrified vehicles that do not have a transmission must be enabled only while the brake command is pressed.

When performing electrification, it is necessary to provide a battery charging indicator for the driver, while at the same time the vehicle must not be allowed to start as long as it is connected to the charger (also a requirement of UN Rulebook 100).

When the vehicle to be electrified is equipped with a steering system electric servo booster, the force required to turn the steering wheel of the electrified vehicle shall correspond to that of the vehicle before electrification. In case the vehicle is equipped with a hydraulic servo booster before electrification, an electrically driven hydraulic pump can be installed to provide the necessary servo action.

The cab ventilation and windows defogging system shall have the same performance as in the vehicle before electrification.

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Autonomous
Driving