EH2TA

Education in Hydrogen Technologies Area

HYDROGEN VEHICLES WITH FUEL CELLS

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CONTENT

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INTRODUCTION - REASONS FOR USING HYDROGEN AS A VEHICLE FUEL

Reasons for using hydrogen as a fuel in vehicles – reducing the consumption of fossil fuels and the production of harmful emissions

It is expected that in the future, production of fossil fuels (mainly oil and natural gas) is will decline, and their prices will continue to rise. One alternative fuel to replace them could be hydrogen, as its reserves in water are almost inexhaustible.

The heat of combustion of hydrogen was noticed by natural scientists and technicians a long time ago, but its industrial use did not begin until the early 20th century, primarily for welding or as a hydrogenating and reducing agent. The first experiments with using hydrogen as a fuel for rocket engines started in the early 1950s and did not reach the implementation phase until the mid-1960s.

The main advantage of hydrogen as a fuel is its clean combustion. When hydrogen is used in internal combustion engines or in fuel cells, it produces thermal, mechanical, or electrical energy and a harmless byproduct: water. It does not produce any waste CO2 or other combustion by-products that result from the combustion of solid, liquid, or gaseous hydrocarbon fuels. CO2 is the main component of greenhouse gases, and the hydrogen economy aims primarily to limit their formation."

Hydrogen reserves in water are nearly inexhaustible. It has a high energy density per unit weight and can be transported and stored. From an environmental perspective, burning hydrogen is cleaner than burning fossil fuels, and produced water is not accompanied by toxic compounds or greenhouse gases.

On an industrial scale, hydrogen is produced on the one hand by petrochemical processes, including coal gasification (accounting for 90% of production), and through electrolysis of water. It is also an important byproduct or component of gases generated by refineries, coking plants, and electrochemical production based on aqueous solutions of inorganic acids or salts.

Hydrogen is a colorless, tasteless, and odorless gas and is the lightest of all gases.

Chemical formula: H2

CAS number: 1333-74-0

EC number: 215-605-7

UN number: 1049

Hydrogen is the simplest and most abundant element in the universe, accounting for about 75%. Although molecular hydrogen (H2) is rare on earth, it can be found bound in water and hydrocarbons.

However, its low density presents storage and distribution challenges. As liquification is only possible only after cooling below the critical temperature of 33.15 K

The main objective of adopting hydrogen economy is to achieve climate neutrality by 2050.

The importance of the of hydrogen has been repeatedly emphasized in strategy documents for the Green Deal, including the "The Hydrogen Strategy for a Climate Neutral Europe".

Physical properties

Molecular weight: 2.02 g

Boiling point: -252.9 °C

Triple point: -259.2 °C

Critical temperature: -239.9 °C

Critical pressure: 12.8 atm

Gas density at 0 °C and 1 atm (air = 1): 0.089 g/l

Gas density at 25 °C and 1 atm (air = 1): 0.069 g/l

Auto-ignition temperature in air at 1 atm: 570 °C

Although hydrogen is relatively inactive at ambient temperature, it reacts with most other elements at elevated temperatures. For instance, hydrogen can reduce metal oxides at elevated temperatures. This reactivity at elevated temperatures is widely used in most industrial hydrogen installations outside the energy sector.

Therefore, hydrogen can be considered incompatible with oxidants such as air, oxygen, and halogens. For example, fluorine and hydrogen react at a temperature of 250 °C in the presence of impurities. Mixtures of chlorine and hydrogen are prone to explosion when exposed to light, and lithium burns in a hydrogen atmosphere.

Hydrogen is an extremely flammable gas and burns in air with a pale blue flame that is practically invisible in concentrations from 4 to 75% by volume under standard conditions.

Moreover, hydrogen is processed at elevated pressures. If there is a leak, the hydrogen causes an inverse Joule-Thompson effect, resulting in the escaping gas getting hot enough to ignite immediately. This increases the low minimum ignition energy of the flammable mixture of hydrogen and air, making it more sensitive to the probability of ignition compared to other flammable gases.

The likelihood of ignition is also higher compared to other flammable gases because the small size of the hydrogen molecule allows it to leak more easily through small holes. This property is the reason why equipment intended to contain hydrogen is sometimes tested for tightness with helium, an inert gas, as its molecule size is comparable to that of hydrogen.

Because hydrogen is lighter than air, the gas easily rises into the atmosphere, unlike propane, which remains at ground level, increasing the risk of explosion. Practice shows that hydrogen does not ignite in open air.

Therefore, the main danger associated with the use of hydrogen is the formation of flammable mixtures with air, which, when exposed to an ignition source, can lead to a fire or possibly a deflagration. The gap that a hydrogen flame can spread in is much narrower than most other gases, making it very difficult to design electric motors that are sufficiently "tough" for use in atmospheres where a flammable mixture of hydrogen and air may be present.

Questions:

1. Why is there a drive to replace fossil fuels with hydrogen?
2. When and for what purpose did hydrogen begin to be used industrially?
3. When did hydrogen begin to be used as a fuel for rocket engines?
4. What is the main advantage of hydrogen as a fuel?
5. What are the other advantages of hydrogen as a fuel?

1 HYDROGEN AS A SOURCE OF ENERGY

OBJECTIVES:

In this chapter, we will briefly look at ways of producing hydrogen from fossil fuels, or by electrolysis of water using electricity obtained, for example, from renewable energy sources.

KEYWORDS:

Hydrogen production, fossil fuel, steam reforming, partial oxidation, electrolysis, alternative sources

You can learn more about hydrogen production in another module, but for the purpose of a general overview in this section, we mention it here as well.

One of the alternatives for replacing hydrocarbon fuels is the use of hydrogen, which is a substance that hardly occurs on its own in nature and therefore needs to be produced.

One possible way of obtaining it is from fossil fuels such as oil, natural gas, and coal, but this is contrary to the reduction of the production of these fuels.

The second possible way is to use electrolysis of water, which requires a significant amount of electrical energy that must be generated in some way, such as in conventional power plants, which, however, consume fossil fuels.

Hydrogen production can be divided into:

- production of hydrogen from fossil fuels
- production of hydrogen by electrolysis

- production of hydrogen from biomass

- production of hydrogen from alternative energy sources.

1.1 PRODUCTION OF HYDROGEN FROM FOSSIL FUELS

1.1.1 STEAM REFORMING OF NATURAL GAS

- currently the most widespread method of hydrogen production

Process:

1. desulfurization of natural gas
2. methane reforming with steam
3. CO conversion
4. CO_2 scrubbing
5. methanization

Advantage: lowest production costs (36-38% lower than hydrogen production through partial oxidation of hydrocarbons and coal gasification).

1.1.2 PARTIAL OXIDATION OF HYDROCARBONS

- The second most common way of producing hydrogen in the world. Both gaseous and liquid raw materials obtained from primary and secondary oil processing can be used as raw materials.

- Raw material is gasified with steam and oxygen at temperatures of 1300-1430 °C.

- The high temperature and the absence of a catalyst make it possible to use heavy oil fractions, fuel oils, vacuum residues and propane asphalts as raw materials, which are characterized by significant soot formation.

Disadvantage: formation of carbon monoxide along with carbon dioxide.

1.1.3 COAL GASIFICATION

- The production of hydrogen through gasification of coal is similar to its production through partial oxidation of petroleum residues.

Process:

1. production of synthesis gas through gasification of coal with oxygen or air and steam in a gasification generator

2. cooling of the hot synthesis gas
3. gas purification and separation of hydrogen from the gas

Disadvantage: higher cost of production

1.2 PRODUCTION OF HYDROGEN BY ELECTROLYSIS OF WATER

- Classic, time-proven production technology

Process:

- An electric direct current passing through two metal electrodes immersed in water is used to to dissociate water into gaseous hydrogen and gaseous oxygen.
- The production of hydrogen by electrolysis can also be performed using electrical energy produced from renewable sources such as solar, wind energy, hydro, or nuclear energy.

1.3 PRODUCTION OF HYDROGEN FROM BIOMASS

The production of hydrogen from biomass can be divided into two processes:

- steam reforming of biomass – pyrolysis
- biotechnological processes – fermentation

Another possible method is the use of biomass derivatives, such as bioethanol and biogas, but here it is better to use these derivatives directly as fuel.

The substrates processed by this method range widely from solid municipal waste, waste from the food industry, oil, to purposefully grown or waste agricultural biomass.

1.4 PRODUCTION OF HYDROGEN FROM ALTERNATIVE ENERGY SOURCES

As it was described above, water electrolysis can also be performed using electricity produced from renewable sources.

The most promising source of energy in this area is solar energy. To enhance the efficiency of hydrogen production, new methods of water electrolysis are being developed, such as:

- high temperature electrolysis (thermolysis)
    - part of the energy is supplied as electrical energy, while the rest is supplied as heat
    - the advantage is an increased process efficiency due to reduced electricity consumption
- thermochemical cycles

- water is split into oxygen and hydrogen through a series of chemical reactions, triggered by heat or a combination of heat and electricity in hybrid cycles (the most well-known being the Westinghouse company's thermochemical cycle – sulfuric acid hybrid cycle).

1.5 REFERENCES

HROMÁDKO, Jan. Speciální spalovací motory a alternativní pohony: komplexní přehled problematiky pro všechny typy technických automobilních škol. Praha: Grada, 2012. ISBN 978-80-247-4455-1.

1.6 END-OF-CHAPTER QUESTIONS:

1. Why is it necessary to produce hydrogen in order to use it as an energy source?
2. Why is hydrogen needed for energy production?
3. What is the advantage of steam reforming of natural gas?
4. What is the feedstock in partial oxidation of hydrocarbon?
5. What is the disadvantage of partial oxidation of hydrocarbon?
6. What is the disadvantage of producing hydrogen by coal gasification?
7. What is the process of hydrogen production by electrolysis of water?
8. What is fermentation?
9. What substrates are used to produce hydrogen from biomass?
10. Electrolysis of water can also be done using electricity generated from renewable sources. List some. Which of these sources is the most promising?
11. What are the new variants of water decomposition?

2 FUEL CELLS

OBJECTIVES:

The objective of this chapter is to understand the principle of power generation using a fuel cell and to learn about its different types.

KEYWORDS:

fuel cell, oxidizing agent, hydrogen, membrane, solid oxides

2.1 INTRODUCTION

All vehicles with internal combustion engines produced today burn fossil fuels, thus impacting the environment negatively. In comparison, electric battery vehicles offer numerous advantages. They are quiet, emit no harmful substances into the environment, do not require a transmission for operation, and their electric motors are highly efficient. However, one major drawback of battery-powered vehicles is their heavy weight and limited battery lifespan. Fuel cells are presented as an alternative to these heavy batteries. Vehicles powered by fuel cells also have a reduced impact on the environment, are not reliant on fossil fuels, and are highly efficient. Fuel cells can provide unlimited energy under specific conditions and their power output can be easily adjusted within a wide range.

2.2 HISTORICAL DEVELOPMENT

Decomposition of water into oxygen and hydrogen using an electric current was first demonstrated in 1802 by Sir Davy Humphrey. The conclusion of his experiment was that a small electric charge still existed on the electrodes even after the source of the electric current has already been disconnected. However, he was unable to adequately explain this phenomenon.

The basic principle of the fuel cell was discovered in 1838 by the Swiss scientist Christian Friedrich Schönbein, who described it in one of his publications a year later. The article discussed the discovery of ozone and the reaction between oxygen and hydrogen that produced an electrical potential at the electrodes. Sir William Grove, who is considered the "father" of fuel cells, built the first working prototype based on this theoretical work. In 1843, he further wrote about this topic in an article focused on storing electrical energy using gases.

The term "fuel cell" was probably first used by Charles Langer and Ludwig Mond in 1889, when they attempted to develop a cell powered by lamp gas. Despite improvements by William Jacques, who used phosphoric acid as an electrolyte, the cost of manufacturing this cell remained too high. After the invention of the dynamo by Werner von Siemens, the fuel cell fell into obscurity and it wasn’t until 1952 that the first usable prototype with a power output of 5 kW was presented by its inventor, Francis Thomas Bacon. This prototype used potassic hydroxide as the electrolyte.

In the 1960s, the hydrogen fuel cell became an important and highly addressed topic due to space research, because it has a more favourable energy-to-weight ratio compared to other energy sources. Fuel cells were installed, for example, on Apollo spacecrafts and they also powered the Space Shuttles, with each orbiter housing three fuel cells, each with a continuous output of 7 kW and a peak output of 12 kW. One of the main advantages was that the waste product of the hydrogen-oxygen cell was pure water, which could be used in the shuttle's water system.

Since the end of Second World War, the German Navy has been prohibited from using nuclear submarines, and as a result, it was looking for an alternative source of electrical energy. One solution was the use of fuel cells, with cells producing 30 kW of power used in older generations of vessels, and cells producing 120 kW of power used in newer ones. From 2005 to 2008, the first hydrogen highway, called HyNor, with a length of 560 km was put into operation in Norway.

In 2008, a network of hydrogen refuelling stations and fuel cell car rentals was put into operation in the cities of Los Angeles, San Francisco and Las Vegas in the United States. These are Honda FCX Clarity vehicles with a 100 kW PEM fuel cell. In June 2009, the TriHyBus was put into operation in the Czech Republic, which is the first bus with a fuel cell in the former Eastern Bloc. In October 2009, the first hydrogen filling station in the countries of the former Eastern Bloc was commissioned in Neratovice.

2.3 PRINCIPLE

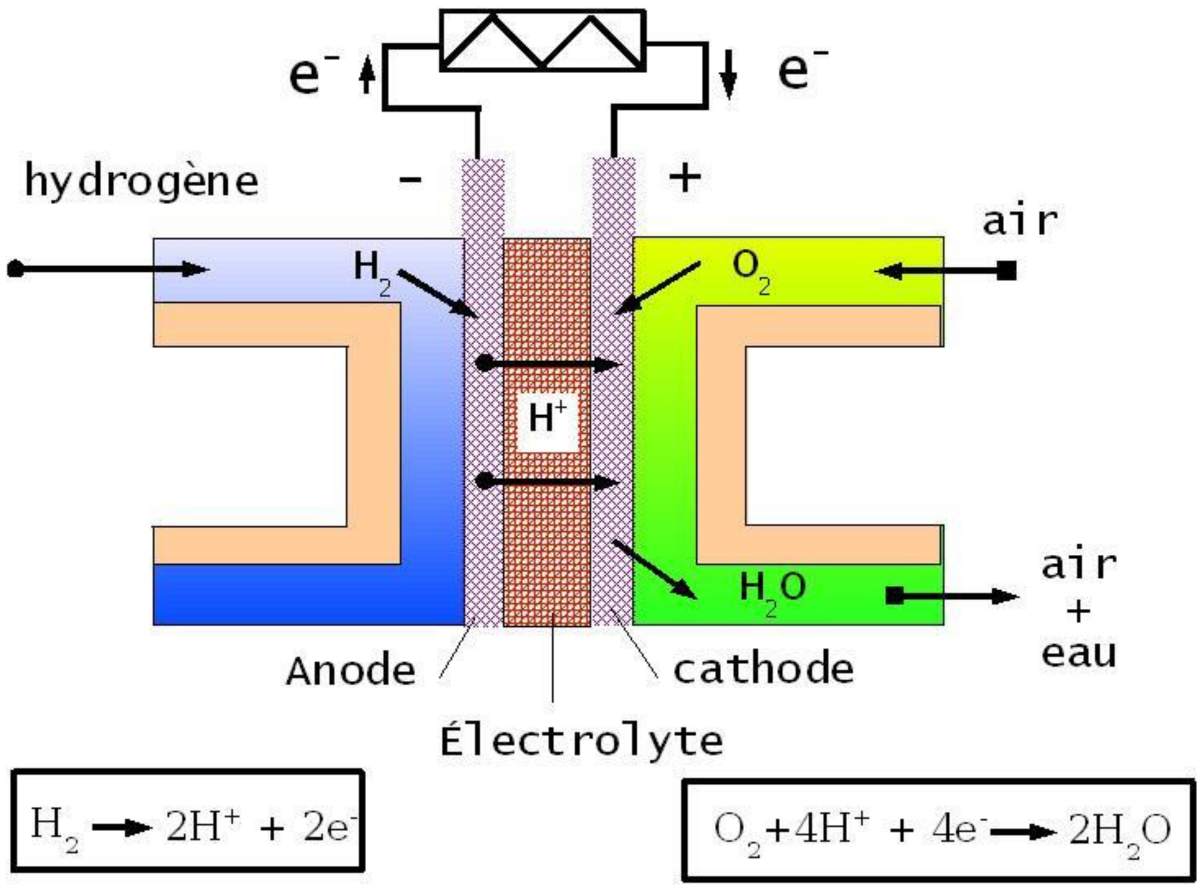
Fuel cells are generally defined as electrochemical devices and their function is to convert hydrogen (fuel) and oxygen (oxidizer) into electrical energy. These galvanic cells contain two electrodes separated by a membrane or an electrolyte. The fuel (hydrogen) is supplied to the positive electrode, while the oxidizing agent (oxygen) is supplied to the negative electrode. Electrons are created at the positive electrode (anode)and flow through an external electrical circuit to the negative electrode (cathode), generating an electric current. In theory, a fuel cell can operate continuously as long the supply of fuel or oxidizer to the electrodes is not interrupted.

There are many combinations of fuel and oxidizer. For example, an oxy-hydrogen cell uses hydrogen as fuel and oxygen as an oxidizer, producing pure water as a waste product. Other cells use hydrocarbons and alcohols as fuels. Instead of pure oxygen, air, chlorine, or chlorine dioxide can be used as oxidizing agents.

Electrodes can be made of carbon (nanotubes) or various metals, and their efficiency can be increased by coating them with catalysts, such as palladium or platinum.

Different acids, mostly phosphoric acid (H3PO4), or bases, most commonly potassium hydroxide (KOH), ceramics, or membranes can serve as electrolyte. In specific fuel cells, gas under high pressure is used as the electrolyte. The most widely used electrolyte today is KOH, which was already used in cells in the Apollo project. However, the disadvantage of this electrolyte is that the oxidizer must be cleaned of CO2 to prevent carbon dioxide from reacting with it, as the resulting potassium carbonate would cease to fulfil the function of the electrolyte.

The resulting electrical voltage is theoretically around 1.23 volts, and its value depends on the type of fuel used and the quality of the cell. Currently, most commonly used cells typically produce a voltage of 0.5 - 0.95 V. To achieve a higher voltage, multiple fuel cells can be connected in series. The magnitude of the current depends on the surface area of the cell, and commercially available cells today can provide approximately 0.5W/cm^2.



Picture 1 – schematic representation of reactions in a fuel cell (source: https://cs.wikipedia.org/wiki/Fuel cell

The fuel is catalytically oxidized at the anode to produce cations (such as hydrogen to H+). These cations pass through the membrane or into the electrolyte. The released electrons are collected at the anode and travel towards the electrical device. Because electrons carry a negative charge, the electric current flows in the opposite direction, from the cathode (+), through the electrical device to the anode (−). At the cathode, the oxidizing agent is reduced to anions (such as oxygen to O2−), which then combine with cations (for example, hydrogen and oxygen to form water).

2.4 TYPES OF FUEL CELLS

Fuel cells can be classified by their operating temperature into low-temperature and high-temperature cells, or by the electrolyte which they use.

2.4.1 ALKALINE ELECTROLYTE FUEL CELLS (AFC)

These cells are among the oldest, and they use an aqueous solution of alkaline hydroxide (NaOH, KOH) fixed in an asbestos matrix as electrolyte. Their operating temperature can reach up to 230 °C. Pure hydrogen is used as fuel and pure oxygen or carbon dioxide-free air as an oxidizing agent.

In these cells, various types of catalysts can be used, not just those based on platinum. Nickel, silver, their oxides or noble metals can be used. These cells have mainly found use in space or military applications.

2.4.2 POLYMER MEMBRANE FUEL CELLS (PEMFC)

A polymer membrane is used as an electrolyte in this type of a fuel cell. The membrane must be conductive to hydrogen ions (protons). and must be moistened to function properly. Sulfonated fluoropolymers (Nafions) are most commonly used. Platinum is often used as a catalyst, applied in the form of a gas-diffusion layer, to create a gas-diffusion electrode with a fixed catalyst. Hydrogen or methanol is used as fuel and oxygen or air as an oxidizer. The operating temperature of this type of cell is up to 90 °C, making it the best option for powering vehicles.

2.4.3 PHOSPHORIC ACID FUEL CELLS (PAFC)

The electrolyte used in this fuel cell is 100% phosphoric acid, which is fixed in a matrix, such as asbestos, polybenzylimidazole. The operating temperature of these cells is 150–220 °C, and temperatures above 180°C have the advantage of shifting the equilibrium constant in favour of carbon dioxide, eliminating the problem of carbon monoxide poisoning. In this case, we can use gas directly from steam reforming.

Again, platinum is used as a catalyst, and hydrogen, which is generated from fossil fuels through steam reforming, is used as fuel. Air is used as an oxidizer. These fuel cells have found use in cogeneration units.

2.4.4 MOLTEN CARBONATE FUEL CELLS (MCFC)

A melt of a mixture of alkaline carbonates is used as an electrolyte in these fuel cells and their operating temperature ranges between 600-700 °C. The mentioned carbonates form a melt of highly conductive salts.

Expensive catalysts are not required in these fuel cells as internal reforming increases their efficiency, so the fuel doesn't have to be extremely clean. Gas from the steam reforming of fossil fuels or biogas is used as fuel, air is used as an oxidizing agent. These fuel cells are used in power plants and cogeneration units.

2.4.5 SOLID OXIDE FUEL CELLS (SOFC)

In this type of a fuel cell, a ceramic membrane is used as an electrolyte, and there is no need for expensive catalysts. These cells operate at high temperatures (around 800-1000°C), and their efficiency can be increased by using the reaction products in a expansion turbine. Gas from the steam reforming of fossil fuels and biogas, natural gas, or biogas can be used as fuel, and air is used as an oxidizing agent. This type of fuel cell found applications in cogeneration units and power plants.

2.5 END-OF-CHAPTER QUESTIONS:

- What are the advantages of battery-powered vehicles compared to internal combustion engine vehicles?
- Who built the first working fuel cell prototype?
- What is the waste product of a hydrogen-oxygen fuel cell?
- What is one of the biggest disadvantages of electric powered vehicles?
- What is a fuel cell?
- What does a fuel cell consist of?

3 ELECTRIC MOTORS IN VEHICLES

OBJECTIVES:

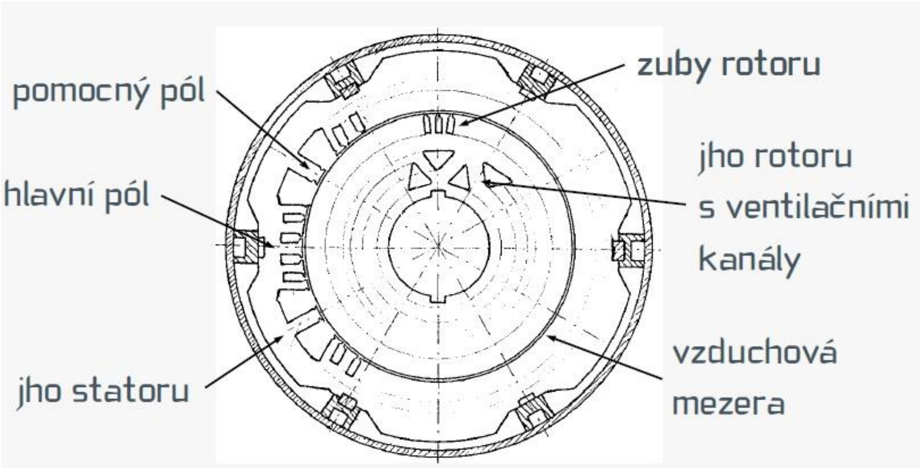
In this section, we will learn about the different types of electric motors for hydrogen vehicles, their design, characteristics, advantages and disadvantages.

KEYWORDS:

stator, rotor, commutator, excitation winding, permanent magnet, torque characteristics, synchronous, asynchronous, reluctance motor

3.1 DC (DIRECT CURRENT) MOTORS

The DC motor is one of the oldest motors, and like any motor, DC motors consist of a stator and a rotor. The stator can be made of permanent magnets or poles that are bolted to the frame and extended at the end with pole extensions. A field winding is then wound around the poles and there may be auxiliary poles and auxiliary windings as well. The rotor is composed of sheets with grooves in which the working winding is placed. The sheets also have ventilation holes. Electric current to the rotor is supplied through brushes that rest on the commutator, which is mounted to the rotor.



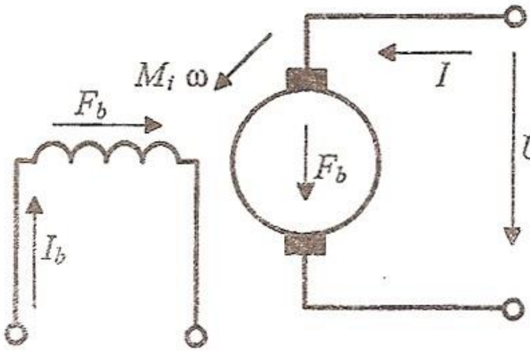
auxiliary pole – main pole – stator yoke – rotor teeth – rotor yoke with ventilation channels – air gap

Picture 2 - Magnetic circuit of a DC motor

The magnetic field excited by the field winding in the stator acts on the magnetic field generated in the rotor due to the current supplied to the field winding through the brushes and the commutator, resulting in a periodic change in the current flowing to the coil, also known as the armature. This, in turn, induces a rotational force, or torque, that constantly acts in the direction of rotation.

According to the way the field winding and armature are connected, DC motors can be divided into motors with external excitation or self-excitation. Motors with self-excitation are further classified into series, parallel (derivative) or series-parallel (compound) motors.

3.1.1 SEPARATELY EXCITED DC MOTOR

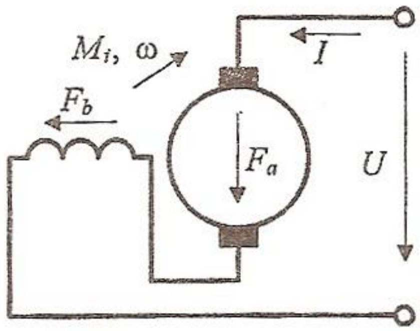


Picture 3 - Schematic diagram of a separately excited DC motor

The field winding is powered by a separate external source, such as an accumulator. Regulation is done by adjusting the voltage on the rotor and the excitation current. DC motor with external excitation has a hard torque characteristic that is especially advantageous for traction purposes. The advantage is its simple and smooth speed control over a wide range and its ability to smoothly transition from driving to braking. However, it has a lower stall torque.

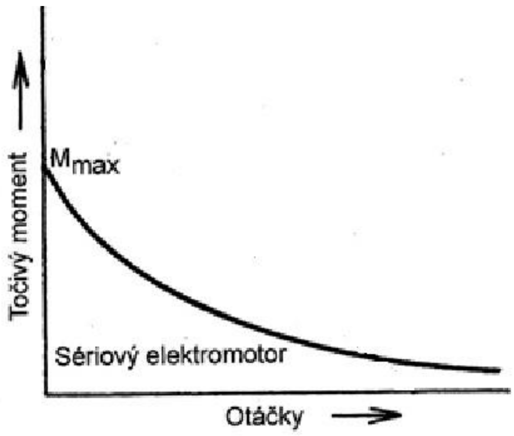
Additionally, with an increased voltage in the entire motor system, higher efficiency is achieved due to reduced voltage drops on the brushes. This also results in smaller current flow in the motor and the connecting lines, leading to benefits such as reduced weight, smaller size, and lower production costs. These motors have high overload capacity, capable of handling 20% more power than the rated continuous power for one hour. During start-up, they can even handle 100% more power for a short time. These motors have been widely used in electric vehicles, as they can be powered directly by the battery.

3.1.2 SERIES DC MOTOR



Picture 4 - Schematic of a series DC motor

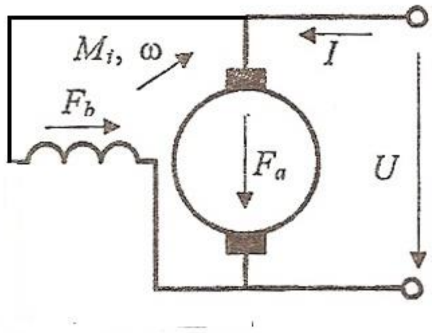
The field winding is connected in series with the armature, so the current in the armature is also the field current. This makes regulation of the motor simple, as its voltage is proportional to the required current value, allowing the power regulator to control the battery voltage by switching or adjusting the frequency. The series electric motor has good starting torque, but the torque characteristic is very soft, with a rapid drop in torque as the RPM increases. If the load is reduced, the RPM can increase to the point where it may cause damage to the motor. Therefore, it is not recommended to operate without a load on the shaft. These motors are used in electric cars and electric traction vehicles such as trains, subways, and trams due to the high torque at low speeds and ability to self-adjust speeds based on the load.



Torque – Revs

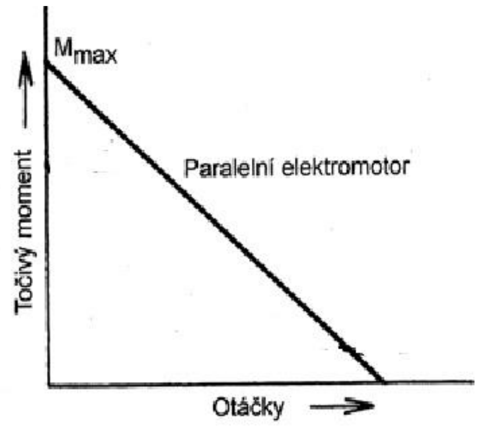
Picture 5 - Torque characteristic of a series DC motor

3.1.3 PARALLEL DC MOTOR



Picture 6 - Schematic diagram of parallel DC motor

The field winding and armature circuit are connected to the source in parallel through separate control elements. This type of electric motor can be easily and smoothly regulated, but to a lesser extent compared to a DC motor with external excitation. They have a harder torque characteristic. The torque decreases more slowly, albeit linearly, with increasing revs. Additionally, the motor also easily brakes. For these reasons, this type of electric motor was used in most electric vehicles.



Torque - Revs

Picture 7 - Torque characteristics of a parallel DC motor

3.1.4 COMPOUND DC MOTOR

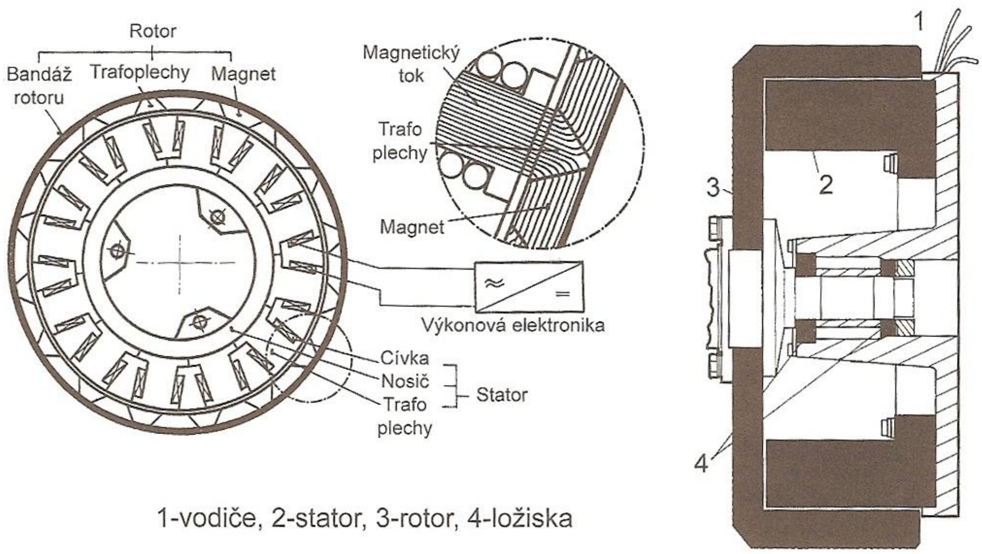
A compound electric motor combines the advantages of both previous electric motors, it has one field winding connected in series and the other in parallel to the armature. The series winding is connected magnetically in correspondingly with the shunt winding and causes a reduction in speed and an increase in torque when the motor is loaded. The shunt winding, on the other hand, limits the speed at idle.

3.1.5 BRUSHLESS DC MOTOR

A brushless DC motor has the rotor and stator positions interchanged compared to a conventional, permanently excited DC motor. The winding is located in the outer stator where permanent magnets are normally found, and the permanent magnets are in the rotor. This construction is similar to that of a permanently excited synchronous motor. The commutator supplies the stator winding with a pulse-modulated direct current, reducing the cost of electronic commutation as the stator winding typically consists of only three or four bundles of windings. These bundles are adjusted in such a way that the flux density of the stator and rotor is approximately phase-shifted by 90°, which securely fixes the rotor's position. Hall probes, an optoelectronic system, or a magneto-resistive system are usually used to achieve this.

Brushless DC motors not only have additional power electronics windings, but also utilize new permanent magnetic materials, such as neodymium-iron-boron and samarium-cobalt, although the latter are still relatively expensive.

The latest advanced solution comes from the Magnet Motor Company, which boasts simple construction, excellent electrical parameters, and a compact weight and size. This motor belongs to the electronic commutation group of synchronous motors with permanent excitation. For all electric motors, the achieved torque is proportional to the magnetic induction in the air gap, the axial length of the rotor, and the square of the air gap radius. The outer rotor design is advantageous because the moment depends on the air gap radius squared. It is composed of pressed laminates with separate, tangentially magnetized magnets of alternating polarity (neodymium-iron-boron), resulting in no rotating electrical parts. Inside there is a stator, which is composed of pressed electrical sheets and forms high-pole coil carriers. The coils are connected to the output of the power electronics, which commutates the currents into the stator winding so that the motor behaves like a DC motor with external excitation. It is the so-called electronic commutation. Regulation is simple and flawless across the entire speed range up to $n = 0$. To handle the tenfold increase in power compared to conventional electric motor designs, the stator winding is cooled by liquid. Additionally, the motor is up to four times lighter than conventional design, and smaller.



left: rotor – rotor bandage, laminates, magnet

middle: magnetic flux, transformer plates, magnet – power electronics – stator – coil, carrier, laminates

right: 1-wires, 2-stator, 3-rotor, 4-bearings

Picture 8 - Schematic and cross-section of the motor from Magnet-Motor company

3.1.6 SUMMARY

DC motors are used due to easy speed control and suitable dynamic characteristics, but they have lower performance and energy efficiency, require more maintenance, and are more expensive.

Advantages of DC motors:

- technically mature
- simply controlled
- cost-effective

Disadvantages of DC motors:

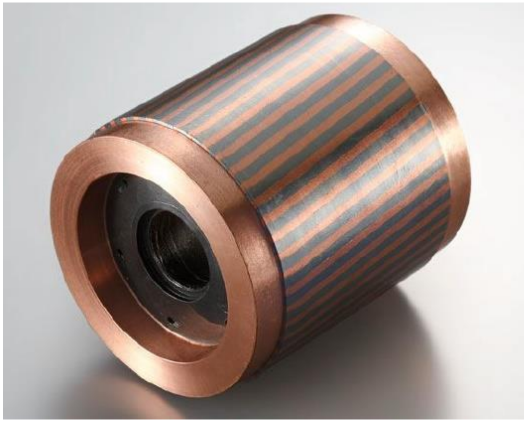
- commutator and brushes are prone to failure and must be maintained
- the maximum peripheral speed is limited by the rotation frequency to approx. 7000 min-1

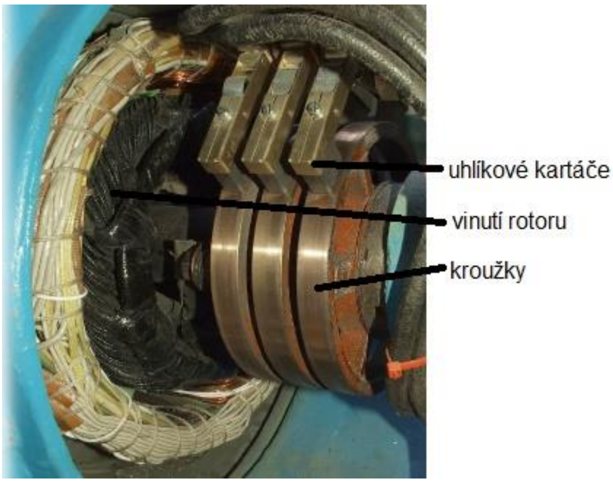
lower efficiency and power density compared to AC motors to regulate all previous types of electric motors, electronic regulation of the power supply to the motor winding using silicon thyristors with a rectangular voltage curve is used. The desired mean current value is set by changing the frequency and amplitude. An increase in field excitation is sufficient for braking within the range of field regulation. As a result, the motor voltage rises above the battery voltage, allowing energy to be fed back into the battery via diodes.

3.2 AC (ALTERNATING CURRENT) MOTORS

AC motors are increasingly replacing DC motors in electric vehicles. The big advantage of AC motors compared to DC motors is that no need to supply current to the rotating rotor, as it is excited by the rotating magnetic field. The magnetic field forces act on the armature and drive it to rotate due to the effect of the induced current. AC motors are categorized as asynchronous motors and synchronous motors, depending on whether the rotor rotates at a different speed or in synchrony with the rotating field of the stator.

4.2.1 ASYNCHRONOUS MOTOR





Carbon Brushes – Winding – Rings

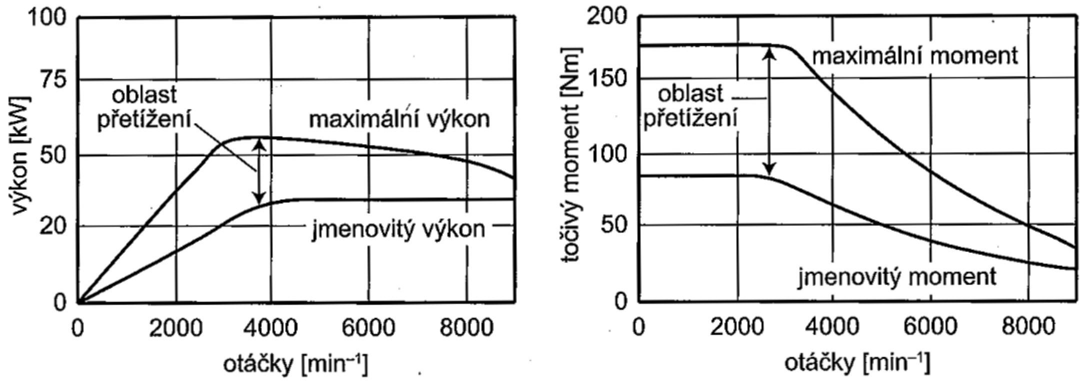
Picture 9 - Cage and ring rotor of an asynchronous motor

The essential advantage of the three-phase asynchronous motor is the elimination of the commutator. The stator is composed of laminates, because a time-varying magnetic flux passes through them. A three-phase stator winding is placed on the poles or grooves. The rotor can be made as a cage or ring. The cage rotor is composed of thick aluminium, bronze, or copper rods connected together in a short way, with laminates filling the interior. The ring rotor is equipped with a winding through which the current supplied by brushes and rings from the outside flows. This design has the resistors located behind the rotor windings, providing the ability to alter operating conditions. In asynchronous motors, the magnetic flux is supplied to the stator by the field winding, but with a rotating voltage of variable amplitude and frequency, which must be derived from the DC voltage of the traction battery. Thus, the direct current from the accumulator must be converted to alternating current. by cyclically switching on thyristors, causing the rectangular waveform changes approximately to a sinusoidal one.

The stator winding is composed of at least three bundles, rotated by 120° from each other, and is powered by three-phase alternating current. Another alternative can also be 3n bundles (n is an integer), offset from each other by an angle of 120°/n. This winding produces a rotating magnetic field with a circular frequency of alternating current ω, or for n bundles with a circular frequency ω/n, meaning it rotates spatially relative to the motor housing.

Compared to a DC motor, an asynchronous motor is significantly smaller and lighter at the same power output, so a Power-to-weight ratio of about 1 kg/kW can be expected. Furthermore, the motor has a simpler design, is robust, maintenance-free, can be heavily overloaded and it can reach up to 20,000 RPM.

Both frequency and voltage must be variable to regulate the traction force and motor speed. Meeting these regulation requirements requires high power circuit costs. Recovery of energy during braking can be done with high efficiency.



Picture 10 - Power and torque characteristics of an asynchronous motor

3.2.1 TRANSVERSE FLUX MOTOR

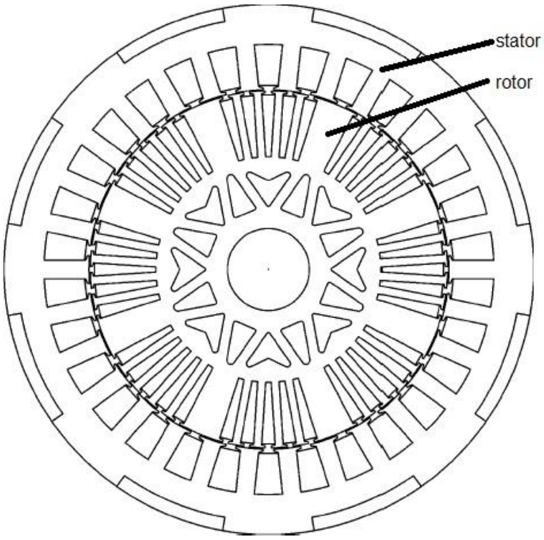
This is a special type of AC asynchronous motor, where the current is supplied to the rotor in the circumferential direction, and the magnetic flux of the stator is not perpendicular to the axis of the rotor but is parallel to it.

3.2.2 SYNCHRONOUS MOTOR

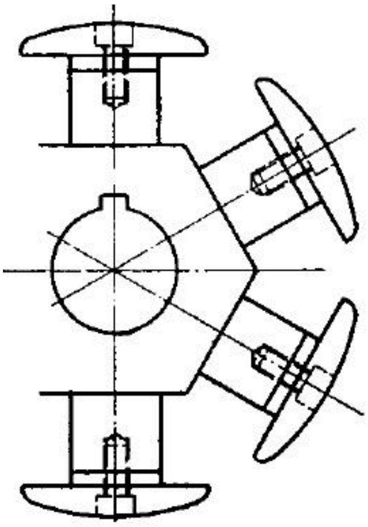
In synchronous motors, the circular frequency coincides with the circulating magnetic field. There are two types of synchronous motors based on the method of rotor excitation, ones with an excitation winding and ones excited by permanent magnets. In the first one, the rotor is equipped with a winding that is supplied with direct current. The rotor can be smooth or with salient poles.

This design's advantage is that a wide range of constant maximum power is achieved due to the variation of direct current.

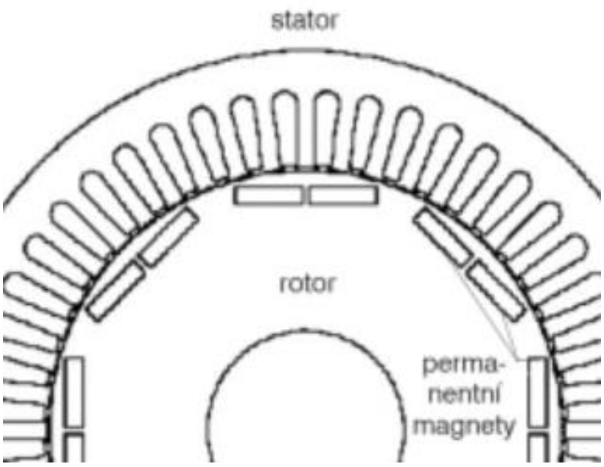
In permanently excited synchronous motors, the magnetic field in the rotor is excited by permanent magnets, which eliminates the need for additional electrical energy. The advantage of this design is its small size and high efficiency.



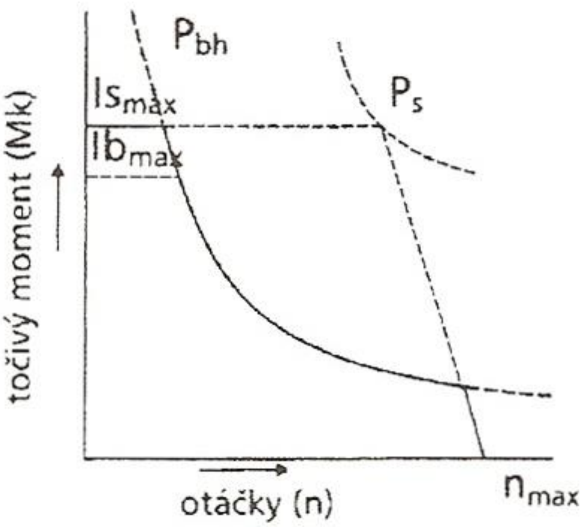
Picture 10 - Smooth rotor



Picture 11 - Outstanding poles (shares)



Picture 12 - Synchronous machine with permanent magnets



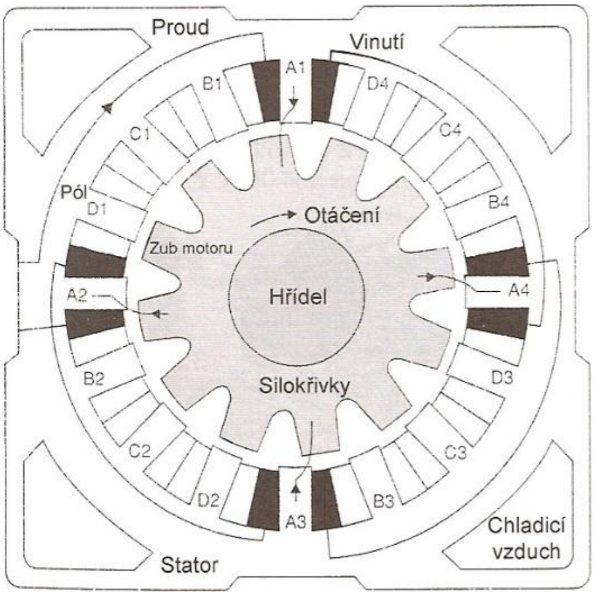
Picture 13 - Torque characteristic of a synchronous motor

3.2.3 Controlled reluctance motor

Reluctance motors are based on the long-known technique of reluctance stepper motors, where changes in magnetic conductivity are utilized depending on the position of the rotor. Although reluctance stepper motors can be produced easily and inexpensively, they have seen limited use for many decades due to their non-uniformity, meaning the torque depends on the rotor position. This disadvantage can be overcome through appropriate control.

There are two main types of reluctance motors: one based on the principle of a synchronous machine with salient poles and the other referred to as a switched reluctance motor, which is based on an electromechanical converter. The first type is a synchronous machine without a field winding and a rotor that has been modified to vary magnetic conductivity as much as possible. Switched reluctance motors are unique in that they cannot function without the aid of electronic circuits, unlike other electrical machines. Depending on the control method used, they can operate in step mode or continuous rotation mode."

A reluctance motor is a special type of AC motor. There are simple coils on the stator powered by voltage of one polarity. There is no field winding or sliding contacts in its rotor. The soft iron rotor has gear-shaped pole extensions.



Picture 14 - Controlled reluctance motor

The principle is that after current is introduced into the corresponding coils, the rotor is adjusted so that the magnetic circuit has minimum magnetic resistance. The speed and torque of the reluctance motor can be very well influenced by power electronics. A reluctance motor starts asynchronously and then runs synchronously.

The concept of reluctance refers to the magnetic resistance that the rotor represents in the magnetic field. Due to the massless tooth gaps in the rotor, the reluctance motor rotor has a very small moment of inertia and thus very high acceleration possibilities.

Advantages of reluctance motors:

- high torque at low speeds
- high efficiency
- robust construction
- low maintenance costs
- stable operation of the motor when one or more phases fail

- high overload capacity and low heat production
- high efficiency and favorable price

Disadvantages of reluctance motors:

- the torque is not uniform (pulsating torque)
- higher noise emissions
- it has high demands on the control and power parts at high speeds

3.2.4 SUMMARY

Advantages of AC motors:

- technically perfect
- compact and robust construction, and therefore maintenance-free
- enable high speeds
- have as high efficiency as DC motors

Disadvantages of AC motors:

- demanding on controls
- higher price

The following table compares the most common traction electric motors and, as it can be seen, all the listed types are suitable for driving vehicles, especially synchronous motors. The best fulfillment of the given characteristic is evaluated with the number 10.

motor	cena	účin-nost	hmot-nost	rozsah Pkonst	přetíži-telnost	spoleh-livost	stav vývoje
stejnosměrný	10	7	6	10	10	7	10
asynchronní	8	8	6	9	10	9	9
synchronní	8	10	7	10	10	9	8
transversální	7	10	8	8	10	10	7
řízený reluktanční	9	6	7	4	10	9	5
stejnosměrný bez kartáčů	8	10	10	8	9	10	8

DC – asynchronous – synchronous – transverse – controlled reluctance – brushless DC

price – efficiency – weight – range of constant power – overload capability – reliability – technical maturity

Tab.: Comparison of different traction electric motor concepts

3.3 END-OF-CHAPTER QUESTIONS:

1. What parts does a DC motor consist of?
2. How do we classify DC motors according to excitation winding connection?
3. What are the advantages of DC motors?
4. What are the disadvantages of DC motors?
5. What does the term asynchronous mean?
6. What does the term synchronous mean?
7. How can the rotor of asynchronous motors be made?
8. What are the advantageous features of an asynchronous motor over DC motors?
9. How can the rotor of synchronous motors be made?
10. What is a reluctance motor?
11. What are the advantages of reluctance motors?
12. What are the advantages of brushless motors?

4 HYDROGEN POWERED VEHICLES

OBJECTIVES:

This chapter is for informational use only to compare the technical parameters of different types of hydrogen powered vehicles.

KEYWORDS:

refuelling, range, performance

Why use hydrogen powered vehicles instead of just using electric powered ones?

Big advantage of hydrogen power over pure electric power is in significantly shorter refueling time.

Picture 15 - Hydrogen refueling (source: https://media.daimlertruck.com/)

4.1 JAPANESE TOYOTA MIRAI IS MASS-PRODUCED HYDROGEN POWERED CAR

Hydrogen to power automobiles can be produced from several different primary sources, which makes it a promising alternative to current sources of energy. Toyota with their Fuel Cell System (TFCS) combined patented fuel cell technology incorporating Toyota FC Stack and high-pressure hydrogen tanks with hybrid technology. This system has much higher energy efficiency compared to internal combustion engines.

Refueling time compared to EVs is much shorter and around 3 minutes. Another difference between hydrogen power and internal combustion engines are zero CO2 emissions. Ride quality is comparable to other automobiles.

4.1.1 DRIVING PERFORMANCE (TOYOTA DATA NOVEMBER 2014)

Vehicle	Cruising range	Approx. 550 km Estimated, according to NEDC Cycle
	Maximum speed	178 km/h
Fuel cell stack	Volume power density	3.1 kW/L (world top level)
	Maximum output	114 kW (155 DIN hp)
	Number of tanks	2

High-pressure hydrogen tank	Nominal working pressure	70 MPa (700 bar)
	Tank storage density	5.7 wt% (world top level)
Motor	Maximum output	113 kW (154 DIN hp)
	Maximum torque	e 335 Nm

Dimensions / seating capacity

Length		4890 mm
Width		1815 mm
Height		1535 mm
Curb weight		1850 mm
Wheelbase		2780 mm
Track (front / rear)		1535 mm / 1545 mm
Minimum ground clearance		130 mm
Interior dimensions	Length	2040 mm
	Width	1465 mm
	Height	1185 mm
Seating capacity		4

4.2 ANOTHER MASS-PRODUCED HYDROGEN POWERED CAR IS HYUNDAI NEXO

Hyundai is among the first mass producers of hydrogen powered cars. Theirs is named NEXO and it's the first hydrogen fuel cell powered SUV. Hyundai managed to develop a car with a superb maximum range of 666 km, refueling storage tanks takes only 5 minutes and has power of 120 KW. System of three connected hydrogen tanks enables thanks to its compact dimensions better use of internal space. Hyundai Nexo was developed to withstand cold temperatures reaching to -30°C and was tested in harsh conditions to guarantee its ability to perform even in winter weather.

Weight of vehicle	1.8 tons
Fuel cell	135 kW
Speed	180 km/h
Maximum range	600 km
Braking	hydraulic system
Tank (hydrogen capacity)	700 bar (6.33kg)

4.3 HYDROGEN BUS SOLARIS URBINO 12

This bus was introduced in Stockholm on 9-12 June 2019 during UITP Global Public Transport Summit.

Solaris Urbino 12 Hydrogen is a zero-emission bus powered by hydrogen fuel cell. It has a range of 350 km and still keeps all advantages of electric power. The bus is characterized by very low noise and the absence of vibrations while in motion. Only product created by the chemical reaction in hydrogen fuel cell is water. Refueling time is only a few minutes, which ensures the flexibility of the vehicle's operation.

Motor	electric portal axle ZF AVE130 2x125 kW
Hydrogen fuel cell	70 kW
Traction batteries	lion
Hydrogen tanks	composite tanks 5x312 l
Charging system	plug-in

4.4 HYDROGEN BUS ŠKODA H'CITY 12

Hydrogen bus from Škoda Group has a maximum range of 350 km. It's characterized by extreme low noise and low vibrations, comfort interior and short refueling time. All that contributes to unparalleled comfort for the passengers and the driver.

Length	12 020 mm
Width	2 550 mm
Height	3 430 mm
Seating Capacity	26—30
Number of passengers	up to 85
Range	up to 350 km
Hydrogen storage capacity	39 g

4.5 HYUNDAI HFC BUS

Was developed in 2018 for the transportation of visitors and staff at the Olympic and Paralympic Games Tokyo 2020.

Weight of vehicle	15 tons
Type of fuel cell	200 kW
Speed	103 km/h
Refueling and drive	400 km
Braking	hydraulic system
Tank (hydrogen amount)	350 bar (40kg)

4.6 DEUTSCHE BAHN’S HYDROGEN TRAIN

Siemens Mobility is developing a new generation hydrogen train Mireo Plus H according to the Deutsche Bahn request and it will be built in in Krefeld factory. It’s one of the most environmentally conscious steps in the transition to zero-emission train transportation. Mireo Plus H achieves ranges of up to 800 km. Power of this locomotive is on the same level as of the electrically powered ones. Its main strengths are high traction power of 1.7 MW, max acceleration of 1.1 m/s^2 and maximum speed of 160 km/h. The three-part train configuration has a max range up to 1000 km.

4.7 END-OF-CHAPTER QUESTIONS:

1. What is the range of refuelling times for cars?
2. What range can cars have?
3. What pressure is used when filling hydrogen powered cars and trucks?