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Control of fuel cell systems in mobile applications

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1. Introduction

A car is one of significant inventions in the history of the human being. With respect to ending crude oil reserves and deepening environment pollution problems, alternative power resources have been started to be found twenty years ago. The aim was and still is searching for power resources less harmful to the environment and providing further long-term carriage and transport development.

Concentrating on the land carriage, it is possible to choose from several types of alternative fuels. Significant alternatives to the current majority use of petrol and diesel oil as fuels to power transport means are hydrocarbon and hydrogen based fuels in form of compressed gases and fluids. Also solar propulsions and compressed air propulsions have been developed. Hybrid and electrical propulsions become still more and more important. The promotion of such alternatives is accompanied by a number of problems which should be addressed in relation to performance, permeability, transport distance ability and cost, as well as transport infrastructure, etc.

Alternative fuels to petrol and diesel oil used as propellants for vehicles mostly comprise:

- Compressed natural gas (CNG).
- Liquefied petroleum gas (LPG).
- Biogas.
- Bio diesel oil and fuels based on rape(-seed) oil methyl-ester.
- Alcohol (ethanol and methanol) using fuels.
- Hydrogen.
- Electric current.

It is evident that "to burn crude oil" is too big luxury since it will be missed by time to the chemical industry which is dependent on it. Currently, compression-ignition engines can use a chemically treated fuel e.g. from rape (-seed) oil known under the name bio-diesel oil. Compared to classic diesel oil, it provides benefits in a combustion process of a thermal motor represented for example in lower quantity of harmful substances in exhaust gases. However, bio diesel oil solves the problem only partially. This is because planting of monocultures at large areas is only possible at remote world parts.

Currently, propane-butane designated as Liquefied Petroleum Gas (LPG) is the most used alternative fuel. Another variant which acquires a large development most recently is

natural gas powered transport means operation. It can be used in a minimally modified spark-ignition motor. Natural gas is a fossil fuel which releases harmful substances into the atmosphere while burning, although in much less quantity. The use of advanced exhaust gas catalysts provides meeting of emission standards for ultra low emission vehicles. They correspond to harmful emissions of an electric vehicle taking into account emission production during electric power generation. Compared to common fuels, harmful substances are produced less by 95 %. Further, Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) can be distinguished. CNG is used for light vehicles while LNG is used for trucks and buses. Like in case of LPG, fuel tanks do not require much space. A natural gas powered vehicle can provide a shorter range and its motor output is lower if compared to the petrol or diesel oil powered vehicles. A fuel supply and pumping system is more demanding too.

The electrical vehicle is powered by an electric motor and produces minimum of harmful substances in operation. The electromotor is supplied from electrochemical accumulators. A development of electric drives in transport is currently prevented from by small one charge range, long charging time and low service time, big weight and high price of inbuilt electrochemical accumulators. It is rightly there, at a level of electrochemical accumulators, where majority environment loading by harmful substances should be found. Significant benefits comprise minimum air emissions in the electrical vehicle traffic, its silent run and low maintenance cost. Aiming to solve the problem of its limited distance reach, the electrical vehicle can be equipped by an electrical motor and combustion motor. Transport means using a hybrid propellant use electric power as a propellant for small distances and at not demanding terrains. A combustion motor is only used at demanding terrain and for long distances. In this way, the performance and distance range are optimized providing also environment friendly traffic, low noise and cost. They are rightly hybrid drive systems which may find application in transport for some transient period. The aim is such their combination that their specific benefits are used as much as possible. Currently, hybrid powered transport means fabricated in a number of car producing factories all over the world. In the future, a hybrid propulsion could become a high quality alternative provided a suitable electromotor power source, i.e. accumulator, is developed.

However, the top perspective is provided by the electromotor drive due to its suitable moment characteristics with a fuel cell current source which transfers the chemical fuel power (hydrogen or hydrocarbons) directly to the electric power. The experience acquired in natural gas powered vehicles operation serves to development of perspective hydrogen powered vehicles. Currently, hydrogen handling is problematic, and its power demands are even higher than hydrocarbon handling. It should be cooled up to the temperature of -253°C in fluidization. Unfortunately, the hydrogen production itself is much electric power demanding. Hydrogen priorities comprise that water vapor is its only burning product. However, a way of hydrogen burning in a conventional combustion motor is not long-term perspective because of its low efficiency.

At the present, the many-years research and development of fuel cells is has been prepared to their putting into a series production. Rejected fuel cells in relation to conventional electrochemical accumulators of electric power do not load the environment by heavy metals, and their service life is comparable or longer. Fuel cells produce electric power from hydrogen and oxygen.

Hydrogen can be gained by a chemical reformation from hydrocarbon fuel in unit (reformer) directly connected with the fuel cell. This presents a technical complication, efficiency decrease, increased weight, as well as other problems. However, they are not unsolvable and, therefore, currently almost all big car producing factories deal with development of fuel cells (General Motors, DaimlerChrysler, Ford, Mazda, Honda, Mitsubishi).

1.1 Hydrogen and fuel cells

A base of the power system design is to determine a suitable technology providing high efficiency and minimum surrounding environment pollution by emissions under usual conditions of the surrounding environment, and a choice of a suitable achievable power source, renewable if possible, of a high power content.

This choice is further subject to another selection run mostly comprising social and political, and economic requirements determining a success of the designed power system under competitive market conditions.

The present chapter deals with fuel cells and hydrogen, combination of a highly efficient technology and pure medium with a high power potential.

Hydrogen is colorless gas without any taste and odor. Under normal conditions, atomic hydrogen is significantly reactive (especially with oxygen and halogens). It creates compounds with all elements of the periodic table save noble gases. Despite high reactivity, it needs initialization power to the reaction. It is able to create a special type of a chemical relationship called a hydrogen bond or also hydrogen bridge, when a bound hydrogen atom indicates affinity also to other atoms which it is not bound to by a classic chemical bond. A hydrogen bond with oxygen atoms is then extraordinarily strong, which explains anomalous physical properties of water (high boiling point and melting point, etc.).

Molecular hydrogen is relatively stable and, with respect to a high value of bonding power, also little reactive. Therefore, it bonds with most elements only under increased temperature or in presence of catalysts.

Hydrogen reactions are accompanied by heat release (exothermic reactions), sometimes also by a light effect - burning. Key properties of hydrogen are presented in the Table 1.1.

General				
Name, symbol, number	Hydrogen, H, 1	Heat of vaporization	0.904 kJ · mol ⁻¹	
Element category	Nonmetal	Heat of fusion	0.117 kJ · mol ⁻¹	
Group, period, block	1, 1, s	Specific heat capacity	14 304 J · kg ⁻¹ · K ⁻¹	
Appearance	colorless	Electric conductivity	-----	
Mass concentration in Earth's crust	0.88 %	Thermal conductivity	0.181 5 W · m ⁻¹ · K ⁻¹	
Atomic properties:		Miscellaneous:		
Standard Atomic weight	1.00794(7) g · mol ⁻¹	Concentration of H ₂ for combustion in air	4 ÷ 75 %	

Atomic radius (calc.)	25 pm (53 pm)	Concentration of H ₂ for explosion in air	13 ÷ 59 %
Covalent radius	37 pm	Highest temperature of combustion in air	2 318 °C (at concentration of H ₂ 29 %)
Van der Waals radius	120 pm	Highest temperature of combustion in O ₂	Up to 3 000 °C
Physical properties		Diffusion coefficient	0.61 cm ³ s ⁻¹
Phase	Gas	Electrode potential	0 V (H ⁺ + e ⁻ → H)
Crystal structure	Hexagonal	Electronegativity	2.1 (Pauling scale)
Density	0,0899 kg m ⁻³	Higher heating (calorific) value	2.98 kWh m ⁻³ = 10 728 kJ m ⁻³
Density of liquefied hydrogen	70,99 kg m ⁻³	Higher heating (calorific) value	33,3 kWh kg ⁻¹ = 119 880 kJ kg ⁻¹
Magnetic ordering	Diamagnetic	Ionization energies	1st: 1 312.0 kJ mol ⁻¹

Table 1.1 Key hydrogen properties.

In the nature, hydrogen occurs as a mix of three isotopes, particularly protium (light hydrogen, 1.00794 amu) – 1H, deuterium (heavy hydrogen, 2.01363 amu) – 2H (2D) and tritium (3.01605 amu) – 3H (3T).

Elementary atomic hydrogen (H) occurs on the Earth only rarely. In such form it only occurs mostly in the star space where it amounts to 75 % of the weight, and almost 90% in relation to the quantity of atoms present in the Universe. It occurs only in higher strata in the Earth atmosphere and, due to its extraordinarily low weight, it is gradually released from the atmosphere.

On the Earth, hydrogen mostly occurs in form of two-atom molecules H₂. As for compounds created by hydrogen on the Earth, most of all water is represented which in form of seas and oceans covers 2/3 of the Earth surface. Other compounds are represented by organic compounds. Hydrogen, together with carbon, oxygen and nitrogen, is included into so-called biogenic elements (elements forming basic “building stones” of all living organisms). Because of that, hydrogen can be found practically in all compounds forming the most significant raw material of the current power and organic chemistry–crude oil.

Hydrogen is also a component of any acid; in water it splits off as H⁺ ion and creates an oxion cation H₃O⁺ which determines key properties of a material, e.g.: polymer membranes of fuel cells. Hydrogen creates compounds called hydrides in valence H⁻.

Hydrogen is produced and separated in three ways:

- A. Chemical – production of synthesis gas / CO conversion (steam reforming, partial oxidation of crude oil fractions, coal gasification), reaction of non rare metals with acids and hydroxides.
- B. Electrochemical – electrolysis of alkalized water or water solutions of chlorides of alkali metals.
- C. Physical – adsorption (PSA, TSA), diffusion (membrane technologies, metal hydrides) or fraction condensation (cryogenic technology).

In addition to production, a basic factor indicating hydrogen application is its storage and transport to a destination. Hydrogen is stored and transported in following ways:

1. In form of compressed gas (CH_2) in aluminum, carbon or composite vessels of pressure of up to 600 Bar and power loss in gas compression of up to 15 % from the power the hydrogen contains,
2. In form of fluidized gas (LH_2) at temperatures below -253°C in reservoirs with negative pressure isolations with a power loss to cooling and compression at a level of up to 30 % of power kept in hydrogen,
3. In form of metal hydride and compound with carbon (carbon absorption), more details see (Fromm, 1998),

Other methods have been still in the stage of research, particularly:

Hydrogen storage in a structure from nanofibers – much promising technology with hydrogen storage capacity of up to 70 % of the total system weight,

Hydrogen storage in a form of compound with ferrum oxides (sponge iron),

Hydrogen storage in small glass balls called microspheres, under very high pressure.

A fuel cell is an electrochemical source transforming the power bonded in chemical bonds to usable electric and thermal power. A course and power balance of this transformation mostly depends on a type of a used fuel cell which differs by used material determining its operation temperature.

A basic division of fuel cells mostly depends on a used electrolyte according to which cells are divided into cells with acid or alkali electrolyte.

On anode of a fuel cell with acid electrolyte (fluid, polymer), the hydrogen gas ionizes, releases electrons and forms H^+ ions (protons). On cathode, oxygen O_2 reacts with electrons e^- transported from the electrode and H^+ ions incoming from the electrolyte. Pure water H_2O is a product of the reaction. Processing chemical reactions can be described as follows:

Anode: $2 \text{H}_2 \rightarrow 4 \text{H}^+ + 4 \text{e}^-$

Cathode: $\text{O}_2 + 4 \text{e}^- + 4 \text{H}^+ \rightarrow 2 \text{H}_2\text{O}$

Generally: $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$

In case of fuel cells with alkali (basic) electrolyte, a common reaction is the same like in case with acid electrolyte; however, a reaction on particular electrodes differs. Hydroxyl ions from the electrolyte react with hydrogen on the anode while electrons e^- and pure water H_2O are produced. On the cathode, oxygen reacts with electrons from the external electric circuit and water from the electrolyte while hydroxyl ions (OH^-) are produced.

Anode: $2 \text{H}_2 + 4 \text{OH}^- \rightarrow 4 \text{H}_2\text{O} + 4 \text{e}^-$

Cathode: $\text{O}_2 + 4 \text{e}^- + 2 \text{H}_2\text{O} \rightarrow 4 \text{OH}^-$

Generally: $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$

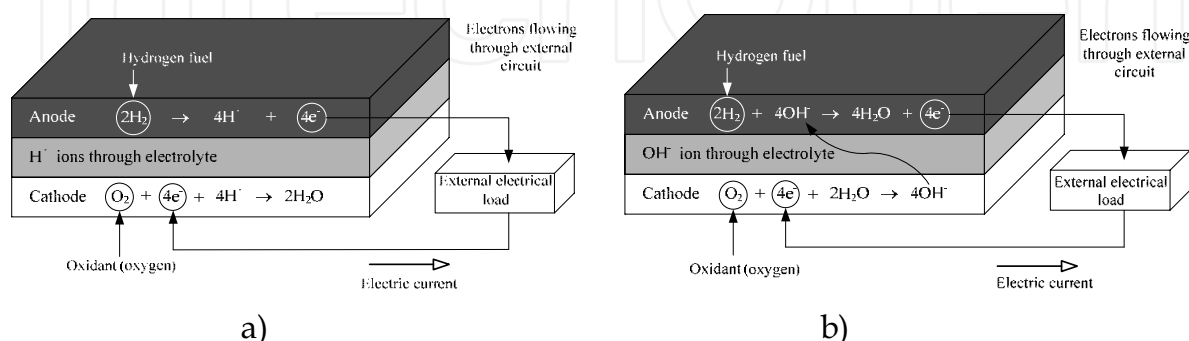


Fig. 1. A reaction on electrodes and charge flow in a fuel cell with acid electrolyte a) and with alkali electrolyte b).

In a point of view of the operation temperature, fuel cells can be divided into high-, medium- and low temperature.

High temperature fuel cells operate under temperatures over 600 °C. Such high temperatures enable spontaneous internal reforming of light hydrocarbon fuels to hydrogen and carbon in presence of water. Reactions taking place on the anode supported by a nickel catalyst provide sufficient heat required for a steam reforming process. The internal reforming further removes a need of a separate unit for fuel processing, and enables a fuel cell to process also other than pure hydrogen fuels. These significant benefits result into the increase of the total efficiency by almost 15 %. High temperature fuel cells also produce high potential waste heat which can be used for cogeneration purposes.

High temperature fuel cells comprise Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC).

Low temperature and medium temperature fuel cells operate usually with temperatures lower than 220 °C. These low temperatures do not allow internal fuel reforming, due to which low temperature fuel cells require an external hydrogen source. On the other hand, they indicate a quick facility startup, and their construction materials are not so much subjected to defects. They are also much more suitable for applications in transport.

Low temperature fuel cells comprise:

Alkaline Fuel Cells (AFC),

Proton Exchange Membrane Fuel Cells (PEM FC) – Direct Methanol Fuel Cells (DMFC).

Medium –temperature fuel cells are operated under temperatures from 200°C to 600°C. Medium temperature fuel cells comprise fuel cells with the phosphoric acid based electrolyte (PAFC – Phosphoric Acid Fuel Cells).

2. PEM Fuel Cells and their characteristics

Mobile applications are a specific field requiring from driving sources particularly a quick start and high system dynamics, minimum of mobile elements (high reliability) or fluid system parts, maximum performance density and efficiency under minimum source mass, etc.

A fuel cell of the PEM type, which is a subject of the following chapter, seems to one of suitable sources.

2.1 PEM Fuel Cell

A description of the construction of a PEM fuel cell

A PEM fuel cell consists of a Membrane Electrode Assembly formed by a proton membrane, catalysts and electrodes ("sandwich structure"). It is the most important part of a fuel cell since all important chemical reactions occur there. A Proton Exchange Membrane or Polymer Electrolyte Membrane is represented by a film of the thickness usually from 50 to 200 µm, which is formed by Teflon fluoro-carbon polymers with a chain ending by a rest of sulphonic acid ($-\text{SO}_3^-$). It means its character is acid. Mostly it is sulphonated fluoro-polymer, usually fluoro-ethylene. A result of presence of these SO_3^- and H^+ ions is a strong mutual attractive force between + and – ions from each molecule. Because of that, molecules of a side chain incline to accumulation inside a total material structure. In terms of a polymer structure, hydrophylic regions (of the group $-\text{SO}_3^-$) are made occurring within a

generally hydrophobic substance. A Proton Exchange Membrane requires sufficient humidification for its proper function, particularly approx. 20 of water molecules per one SO_3^- chain, which provides it's the conductivity of approx. 0.1 S cm^{-1} (Kameš J., 2008). Membrane borders are extended with active electrode area overlaps which provide perfect MEA (Membrane Electrode Assembly) sealing against reaction gas escape.

The Proton Exchange Membrane is covered on both sides by a layer of catalysts of the thickness of units up to tens μm (currently below 0.2 mg cm^{-2}) to support chemical reactions. Usually platinum or nickel is used as a catalyst since they indicate a high electro-catalytic activity, chemical stability and electric conductivity. A catalyst in form of very small particles is applied on a surface of rather bigger particles of a coal powder.

Electrodes, anode and cathode are represented by porous paper, textile or felt with carbon fibers of the total thickness from 0.2 to 0.5 mm comprising PTFE (poly-tetra-fluor-ethylene), which is hydrophobic, due to which product water is expelled to the electrode surface, from where it is evaporated into the surrounding environment. Simultaneously, electrodes serve to more uniform surface density of reaction substances flow to a three phase interface (electrode/catalyst, reactant, electrolyte).

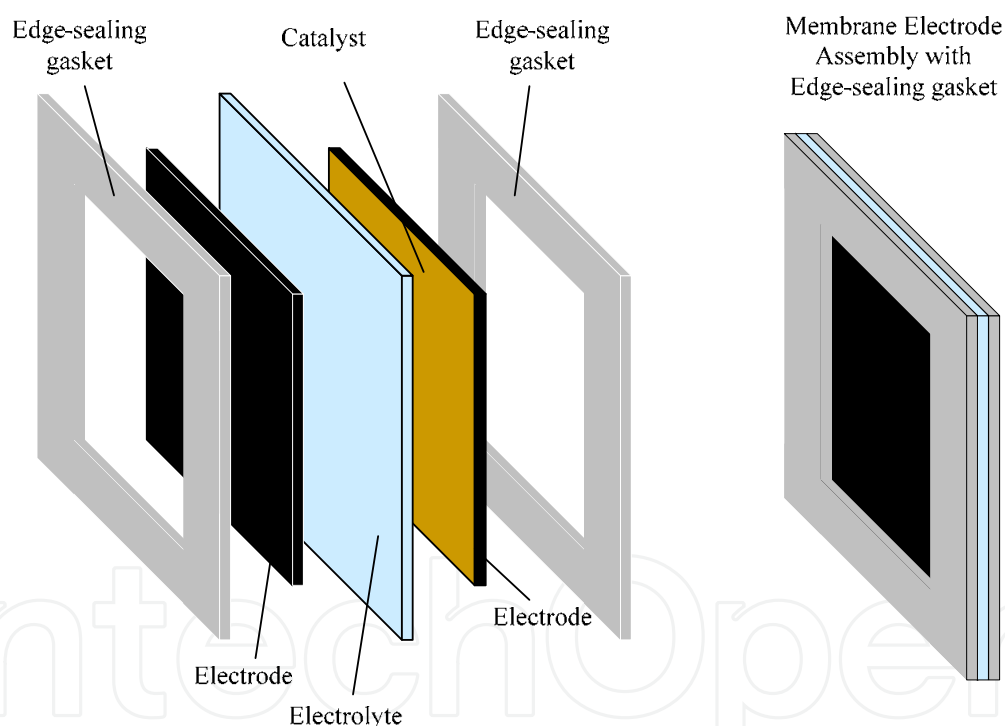


Fig. 2. A structure of an elementary fuel cell – MEA arrangement with end seals.

Bipolar Plates – these plates serving to MEA supply by reactants, discharge of products from MEA and cooling medium distribution, are usually made from graphite (carbon), stainless steel or ceramic materials. They were made by combination of unipolar plates of anode of a cell and cathode of another cell in order to reduce losses in the electric circuit inside a particular cell. On the side of electrodes, they are equipped by channels of a serpentine form providing supply by reaction gas to a membrane arrangement. The stainless steel or graphite containing PTFE is a preferred construction material, with respect to its excellent

electric conductivity, low contamination and relatively low cost. To avoid mixing of the cooling medium with reaction gases, a connection of the anode and cathode plates of two adjacent cells should be equipped by conductive sealing.

End Plates are conductive steel plates comprising inbuilt end electrodes with exit cell clamps. Their sense consists in providing a stabilized cell construction, internal tension increase in the system, power output outlet and electrode cooling.

Auxiliary operation systems and source control (Auxiliary systems) – in addition to a particular system of fuel cells, the electric power source system is equipped by a fuel gas source (hydrogen system), gas oxidation (air or oxygen system), cooling medium source (water system), wetting agents, additive units to monitor and control flows of process media, and other auxiliary process systems to control electric and thermal outputs, set of sensors of physical variables, whole power transformation process control unit. In addition, some systems comprise fuel processing reformers.

For more details see (Larminie J.,2003; Kurzweil, 2003).

2.2 PEM fuel cell polarization characteristics

Required final variable values can be achieved by a suitable construction of a fuel cell (plate/circular system, use and extension of the active catalyst surface, used construction materials, etc.), and setting suitable working points which requires a suitable mathematical physical description of a fuel cell.

This chapter describes a relationship between the efficiency and operation voltage of a fuel cell and basic physical variables of reacting gases (reaction process temperature, process substances pressure and their concentration).

The Gibbs free energy is important for fuel cells, which represents work made by movement of electrons in the external circuit. The cell does not use any work made by a change in the volume of reactants and products on the inlet and outlet from a fuel cell. The enthalpy of formation is a sum of the Gibbs free energy of formation and entropy related power. In terms of enthalpy and entropy, the Gibbs free energy of the system can be expressed as follows:

$$G = H - T \cdot S \quad (\text{J}\cdot\text{kg}^{-1}; \text{J}\cdot\text{kg}^{-1}, \text{K}, \text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}),$$

Where G is the Gibbs free energy of the system ($\text{J}\cdot\text{kg}^{-1}$), H represents the system enthalpy ($\text{J}\cdot\text{kg}^{-1}$), T is a thermodynamic system temperature (K), and S means the entropy of the system ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$).

A following relationship can be applied for one substance mol:

$$\Delta \bar{g}_s = \Delta \bar{h}_s - T \Delta \bar{s}_s \quad (\text{J}\cdot\text{mol}^{-1}; \text{J}\cdot\text{mol}^{-1}, \text{K}, \text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}),$$

Where $\Delta \bar{g}_s$ is a change in the molar Gibbs free energy of the system ($\text{J}\cdot\text{mol}^{-1}$), $\Delta \bar{h}_s$ represents a change in the molar enthalpy of the system ($\text{J}\cdot\text{mol}^{-1}$), T is thermodynamic system temperature (K), $\Delta \bar{s}_s$ is a change in the molar system entropy of the system ($\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$).

Values of particular variables in a range of temperature from 20°C to 1000°C are presented in the Table 2.1.

Fuel cells are not bonded by the Carnot efficiency limit as other combustion cycles. A change in the enthalpy of formation is a basic efficiency limit. If the whole power from the hydrogen

fuel (enthalpy of formation) is transformed to the electric power, then the electromotive voltage reaches the values as follows:

$$E = \frac{-\Delta \overline{h}_f}{2 F} = 1,48 \text{ V}$$

for higher heating (calorific) value ($\Delta \overline{h}_f = - 285.84 \text{ kJ} \cdot \text{mol}^{-1}$); and
= 1.25 V for lower heating value ($\Delta \overline{h}_f = - 241.83 \text{ kJ} \cdot \text{mol}^{-1}$).

The above values express a voltage value which could be possible to reach in case of a 100 % efficient system, depending on a choice of a related value.

The electromotive voltage of a fuel cell in the system without losses can be expressed as follows:

$$E^0 = -\frac{\Delta \overline{g}_f}{2 \cdot F},$$

(V; kJ mol⁻¹, C).

Where E^0 is electromotive open-circuit voltage of a fuel cell (V), Δg_f is a change in the Gibbs free energy of formation of agents (kJ · mol⁻¹), and F is a Farraday constant ($F = 96, 485.341 \text{ C} \cdot \text{mol}^{-1}$).

A maximum available electric power corresponds to changes in the Gibbs free energy, so that

$$\eta_{el \max} = \frac{-\Delta \overline{g}_f}{-\Delta \overline{h}_f} \times 100 \%$$

(-; kJ mol⁻¹, kJ mol⁻¹).

Where $\eta_{el \max}$ is a maximum electric efficiency of a fuel cell (-), Δg_f is a change in the Gibbs free energy of formation of agents (reagents and reactants, kJ mol⁻¹), and Δh_f is a change in the molar enthalpy of formation of agents (reagents and reactants, kJ mol⁻¹). A comma above a lower case letter indicating a variable means that a respective value is expressed in unit x per 1 mol of the substance.

This efficiency limit is designated as thermo-dynamical efficiency.

Temperatur e (°C)	h_{fH_2O}	h_{fH_2}	h_{fO_2}	Δh_{fH_2}	s_{H_2O}	s_{H_2}	s_{O_2}	Δs_{H_2}	Δg_{fH_2}	η	E^0
	kJ · mol ⁻¹			kJ · mol ⁻¹	J · mol ⁻¹ · K ⁻¹			J · mol ⁻¹ · K ⁻¹	kJ · mol ⁻¹	%	V
20	-242,0	-0,1	-0,1	-241,8	188,26	130,11	204,64	-44,17	-228,8	94,64	1,186
30	-241,7	0,1	0,1	-241,9	189,39	131,07	205,63	-44,49	-228,4	94,42	1,184
40	-241,3	0,4	0,4	-242,0	190,49	132,00	206,59	-44,81	-227,9	94,20	1,181
50	-241,0	0,7	0,7	-242,1	191,55	132,91	207,51	-45,12	-227,5	93,98	1,179
60	-240,6	1,0	1,0	-242,2	192,58	133,79	208,41	-45,42	-227,0	93,75	1,176
70	-240,3	1,3	1,3	-242,3	193,58	134,65	209,29	-45,72	-226,6	93,52	1,174
80	-240,0	1,6	1,6	-242,4	194,55	135,49	210,14	-46,00	-226,1	93,30	1,172
90	-239,6	1,9	1,9	-242,5	195,50	136,30	210,97	-46,29	-225,7	93,07	1,170
100	-239,3	2,2	2,2	-242,6	196,42	137,09	211,78	-46,56	-225,2	92,84	1,167

200	-235,8	5,1	5,3	-243,6	204,58	144,03	218,97	-48,93	-220,4	90,50	1,142
300	-232,3	8,0	8,4	-244,5	211,37	149,62	224,99	-50,75	-215,4	88,10	1,116
400	-228,7	10,9	11,6	-245,4	217,25	154,32	230,19	-52,17	-210,3	85,69	1,090
500	-224,9	13,9	14,9	-246,2	222,49	158,40	234,78	-53,30	-205,0	83,26	1,062
1 000	-204,1	29,1	32,4	-249,3	243,11	173,53	252,11	-56,47	-177,4	71,16	0,919

Table 2.1 An example of values $\Delta \overline{h}_s$, $\Delta \overline{s}_s$ a $\Delta \overline{g}_s$ for a chemical reaction between hydrogen and oxygen passing in a fuel cell of the PEM type in a range of temperatures from 20°C to 1000°C.

Not the whole fuel supplied into a fuel cell can be utilized. Some fuel passes through a fuel cell without taking part in the reaction. If this is the case, a coefficient of the fuel use, μ_f , can be defined, corresponding to a portion of electric power of a fuel cell and electric current which would be gained provided the whole fuel passed through the reaction. A suitable value of this coefficient equals 0.95.

The impact of a partial pressure of concentration and temperature of particular reacting substances to voltage in no-load running of a fuel cell is evident from, the following equation:

$$E = E^0 + \frac{R \cdot T}{2 \cdot F} \cdot \ln \left(\frac{\alpha \cdot \beta^{1/2}}{\delta} \cdot P^{1/2} \right) = E^0 + \frac{R \cdot T}{2 \cdot F} \cdot \ln \left(\frac{\alpha \cdot \beta^{1/2}}{\delta} \right) + \frac{R \cdot T}{4 \cdot F} \cdot \ln(P)$$

(V; V, kJ mol⁻¹ · K⁻¹; T, C mol⁻¹, bar).

Where E is electromotive voltage under particular conditions (V), E^0 is electromotive voltage at standard pressure (V), R is a molar gas constant ($R = 8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is thermodynamic temperature (K), F is a Farraday constant ($\text{C} \cdot \text{mol}^{-1}$), α , β and δ are constants which values depend on molar quantity and concentration of H_2 , O_2 a H_2O ($P_{\text{H}_2} = \alpha \cdot P$, $P_{\text{O}_2} = \beta \cdot P$, $P_{\text{H}_2\text{O}} = \delta \cdot P$), and P is a value of the system pressure (bar) at a supposed ambient pressure of 1 bar.

The above equation is called the Nernst equation. This value provides us a theoretical base and quantitative data for a big number of variables when designing and operating a fuel cell.

The previous paragraphs defined voltage of a fuel cell in no-load running (open circuit voltage) depending on physical parameters of reaction gases and ambient environment. In practice, the real operation voltage of a fuel cell differs much due to power losses in particular member parts.

Four major irreversibilities are defined in a fuel cell depending on their occurrence mechanism.

1. Activation losses – they are caused by a course of reactions taking place on electrode surfaces. A part of generated open circuit voltage (OCV) is lost in chemical reaction control. This voltage loss which is strongly nonlinear can be described for a hydrogen fuel cell by an equation called as a Tafel equation:

$$\Delta U_{act} = A \cdot \ln\left(\frac{i}{i_0}\right) = \frac{R \cdot T}{2 \cdot \alpha \cdot F} \cdot \ln\left(\frac{i}{i_0}\right)$$

(V; J mol⁻¹ K⁻¹, K, -, C mol⁻¹, A cm⁻², A cm⁻²),

Where R is a molar gas constant, T is thermodynamic temperature, a is a coefficient of charge transmission - approx. 0.5 for anode, from 0.1 to approx. 0.5 for cathode (Larminie & Dicks, 2003), F is a Faraday constant, i is a current density, and i_0 is an exchangeable current density. This exchangeable current density i_0 gives the size of current flowing from and electrode to the electrolyte, and vice versa. This parameter is decisive for control of a fuel cell on its electrodes. We aim to make this value as high as possible.

The Tafel equation applies only in case when $i > i_0$.

For a low temperature hydrogen fuel cell using the air with the ambient pressure (0.1 MPa) as an oxidizing agent, a typical value for i_0 equals 0.1 mA · cm⁻² on a cathode, and approximately 200 mA · cm⁻² on the anode (Larminie & Dicks, 2003).

A size of the exchangeable current density i_0 can be influenced by operation temperature increase, increase in pressure of reactants and their concentrations, increased catalysts and change in the electrode surface (area) structure.

2. A fuel passage through the electrolyte and internal current – this power loss occurs due to inability to use the whole power entering the cell. The fuel penetrates through the electrolyte to the cathode, and in a less extent, through electron conductivity of the electrolyte. The electrolyte should only transport ions through a fuel cell. Nevertheless, the passage of some fuel quantity and some number of electrons cannot be avoided and pass through a cell. This component causes significant voltage loss of OCV particularly in low temperature fuel cells. If i_n is a value of internal current density describing passage of fuel and electrons through the electrolyte, then the equation for operation cell voltage, taking into account two above mentioned irreversibilities can be modified as follows:

$$U = E - A \cdot \ln\left(\frac{i + i_n}{i_0}\right),$$

(V; V, A · cm⁻², A · cm⁻², A · cm⁻²).

The internal current density usually reaches units mA · cm⁻².

3. Resistance losses – the fuel cell voltage drop is caused by electric resistance of material of electrodes, bipolar plates, and conductive interconnections which is put in a way of the electrons flow, as well as by resistance which puts the electrolyte in a way of the ions flow. This voltage drop is directly proportional to the current density.

If the value of resistance per 1 cm² of active fuel cell surface is defined, designated by the symbol r and call it the resistivity (surface resistance), then the equation for the voltage drop due to resistance losses ΔU_{ohm} takes a form:

$$\Delta U_{ohm} = i \cdot r,$$

(V; mA · cm⁻², kΩ · cm²)

Where i is the current density, and r is the resistivity (surface resistance) a fuel cell.

4. Mass transport and concentration losses – these power losses follow from a change in concentration of reactants on the electrodes surfaces while using the fuel. This type of losses is also designated as Nernstian. This is because of the relationship to concentrations and due to concentration of reactants modeled by the means of the Nernst equation.

Up to now, no analytic solution of a problem of voltage change modeling sufficiently functioning for all fuel cell cases exists. The voltage drop caused by concentration losses and losses caused by mass transportation ΔU_{trans} is expressed by the empiric equation (Larminie & Dicks, 2003):

$$\Delta U_{trans} = m \cdot \exp(n \cdot i), \quad (V; V, \text{cm}^2 \cdot \text{mA}^{-1}, \text{mA} \cdot \text{cm}^{-2})$$

Where the constant m is usually approx. $3 \cdot 10^5 \text{ V}$ and n constant value approx. $8 \cdot 10^{-3} \text{ cm}^2 \cdot \text{mA}^{-1}$. This equation is applied to reach results similar to measurement results.

Giving the above mentioned voltage drops in the same equation, we can gain a complete equation describing process voltage of a fuel cell depending on the current density i :

$$U = E - \Delta U_{Ohm} - \Delta U_{act} - \Delta U_{trans} = E - i \cdot r - A \cdot \ln\left(\frac{i + i_n}{i_0}\right) + m \cdot \exp(n \cdot i)$$

All variables and constants stated in the equation are stated and described in already before presented equations.

3. Basic fuel cell control

3.1 A structure of a hydrogen circuit (source)

A fuel cell itself is not able of any operation. Operating it, suitable conditions for its activity should be provided – particularly supply of fuel gas, oxidizing agent, humidification, discharge of reagents from the cell, heat discharge, and other supporting processes providing a proper system function.

The characteristics of a fuel cell are often indicated in form of a polarization curve which is the cell voltage dependency on the current density. A difference between an actual cell voltage and ideal voltage depends on losses. Losses which influence a course of a polarization curve are presented in the Chapter 2.2 (Pukrushpan et al., 2004). A characteristic polarization curve course is presented in Fig. 3.

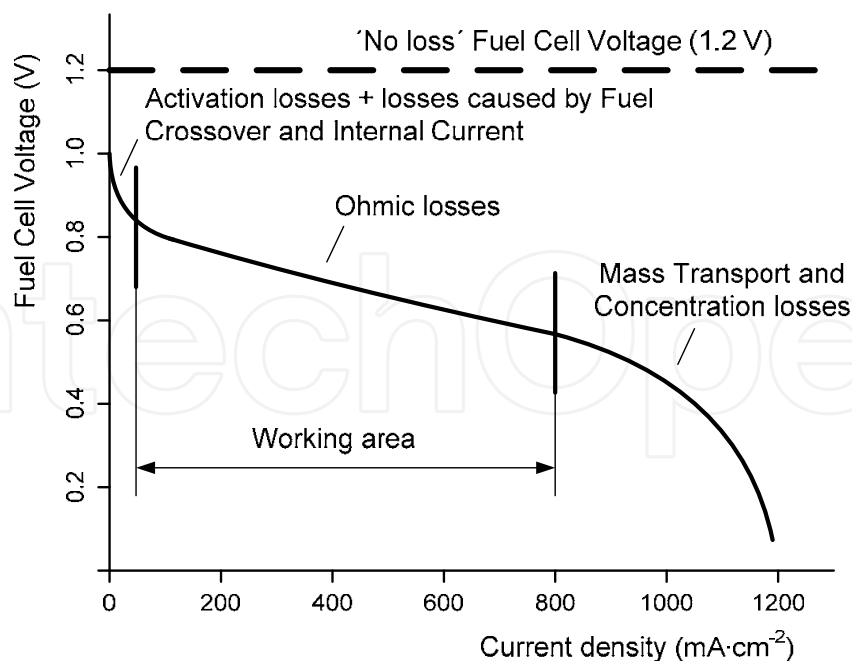


Fig. 3. A fuel cell polarization curve with mentioned main irreversibilities.

A number of factors influences a polarization curve course (See Fig. 4). One of fuel cell control system tasks is to influence the factors so that the fuel cell operation is as much efficient as possible. This particularly covers the factors as follows:

The pressure of the reaction hydrogen and air – increasing the pressure of hydrogen and reaction air usually results into the polarization curve growth.

Fuel cell temperature – increasing the temperature results into the polarization curve growth.

Reaction gases concentration – a concentration of reaction gases in the substance results into a polarization curve growth.

The increase in the reaction gas relative humidity increases a polarization curve course.

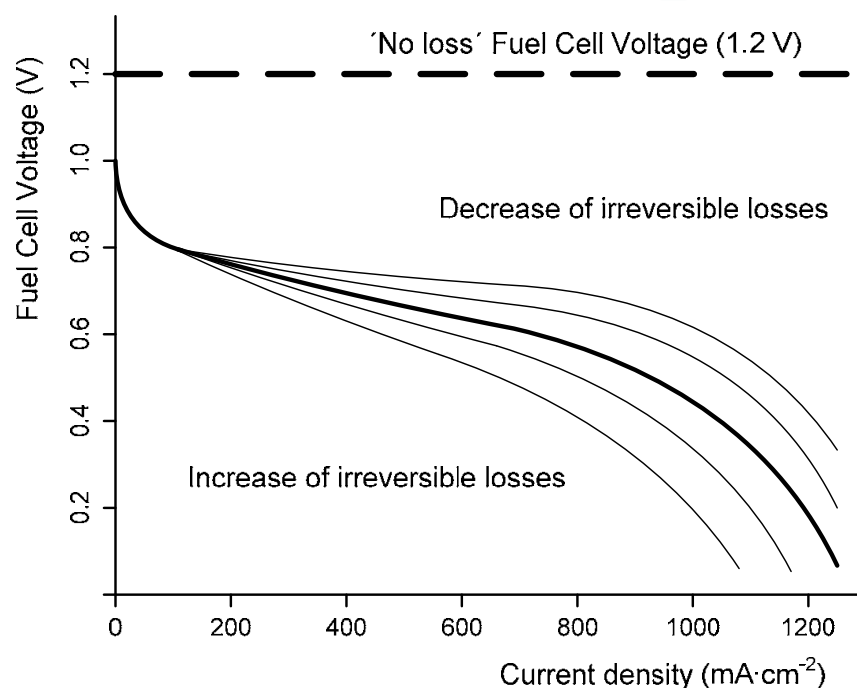


Fig. 4. The influencing of a polarization curve course.

Principal power source circuits with a fuel cell of the PEM type are described on the example of the source system with a Nexa Power Module fuel cell from the company Ballard Power Systems for purposes of the source testing. A summary chart of a hydrogen circuit is evident from Fig. 5.

3.2 Measurement and control system

A programmable automat (PLC) or embedded control system can act as a control unit. Basic fuel cell control principles are presented in Chapter 4.1. A set of sensors of electric and non-electric signals needed for a basic fuel cell system control serves a source of information for the control system. This particularly means voltage on the fuel cell, current taken from the cell, fuel cell temperature, reaction gas pressure, flow rate of reaction gases, etc.

Output block – the output block on the electric output from the fuel cell is represented by a direct current circuit breaker, DC/DC converter 24 V DC/120 V, 24 V DC/12 V DC or

inverter (DC/AC converter) 24 V DC/230 V AC, followed by a single phase electrometer or voltage and current measurement (for the DC output). Parts of the AC output (interconnection with the isolated electric network or electrical power network) are reactance coils (damping of electric surges) and circuit breaker(s). The circuit breaker terminals represent a handover point with the electrification system (isolated network).

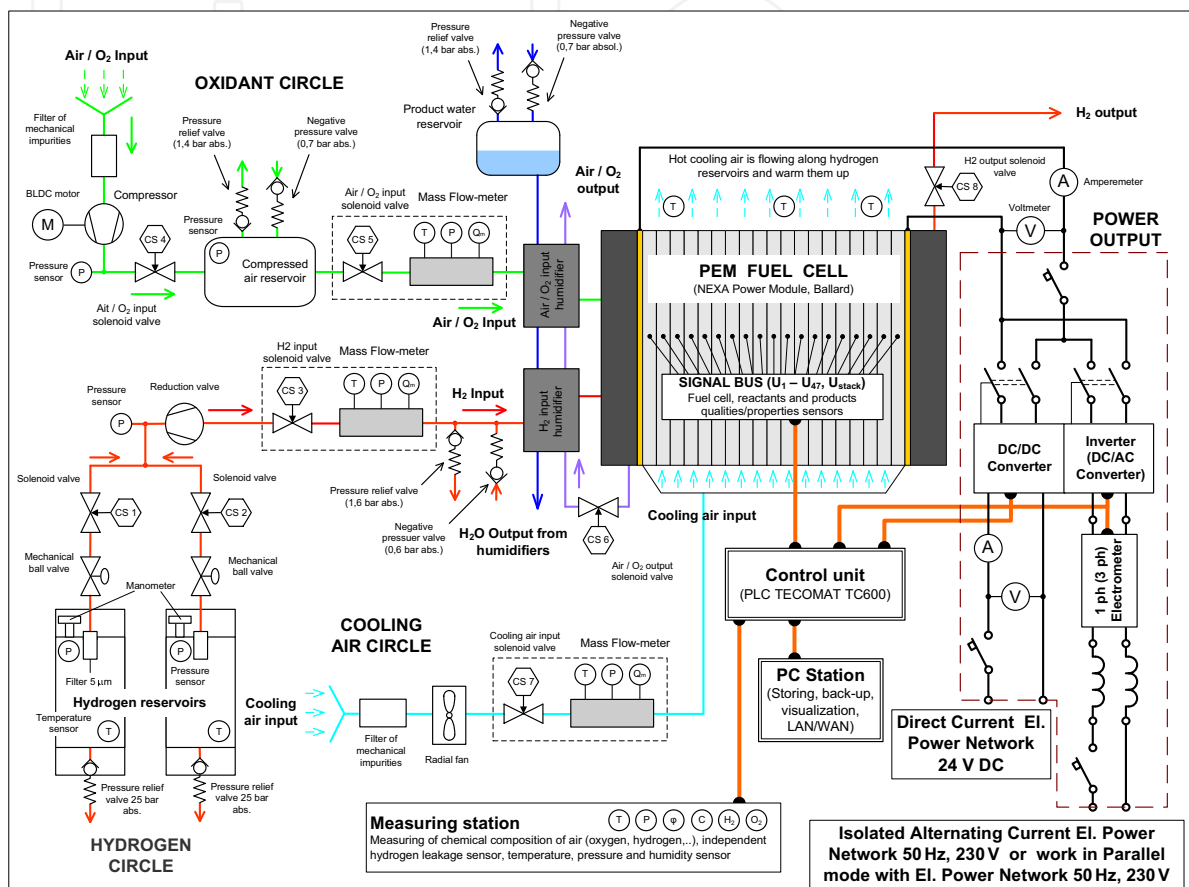


Fig. 5. A summary block diagram of a system with a fuel cell Nexa Power Module designating particular circuits and system elements.

Fuel cell signal bus – for purposes of laboratory monitoring of a source with a fuel cell, it is suitable to install a system of sensors on a fuel cell and its immediate surrounding to monitor voltage of particular elementary fuel cells and the whole stack, internal, surface and cooling air output temperature sensors, concentration of hydrogen in the nearby surrounding of the fuel cell, etc., according to required tested parameters).

A measuring station – represents a reference measurement point in the distance of approx. 5 to 10 m from a source, and its immediate vicinity, in order to find limit conditions in calculations of power balances, and in order to secure the safety of persons and equipment nearby the prototype. The measuring station is equipped by sensors of temperature, pressure and humidity of the ambient air, sensor of concentration of oxygen in the air, and sensor or detector of hydrogen escape into the surrounding environment.

A mobile PC station represented by a portable computer provides acquisition (back-up) and processing of measured data, their visualization on the intranet/internet, and interconnection of a real system with a software model.

3.3 Hydrogen circuit control

Hydrogen is supplied to the power source system from reservoirs with compressed gas or metal hydride, which is heated by the air leaving the cooling fuel cell circuit. Hydrogen reservoirs are followed by a mechanical ball and solenoid valve providing disconnection/separation of a hydrogen circuit from the gas reservoirs (tanks). This is followed by a reduction valve decreasing the hydrogen pressure from reservoirs (up to 25 bar abs.) to the operation pressure (from 1.1 to 1.5 bar abs.). Another element is most usually a mass flow-meter measuring the mass flow-rate (volume flow rate, temperature and pressure) of hydrogen passing the flow-meter (approx. 30 NL/min max.). Still before hydrogen entering the fuel cell, it passes through a humidification unit where it is saturated by water vapor as needed. A solenoid valve is situated at the exit from a fuel cell providing controlled hydrogen discharge from the fuel circuit. The fuel circle can be also equipped by a pressure sensor monitoring the hydrogen pressure in reservoirs and before the hydrogen entry into a reduction valve. Further, the surface temperature of reservoirs with a metal hydride is monitored.

3.4 Reaction air circuit control

A compressor suctions the surrounding air via a filter of mechanical impurities and drives it into a compressed air reservoir. The compressed air reservoir of the volume of approx. 10 - 20 NL serves to stabilization (uniformity) of the air/oxygen flow into a fuel cell. The reservoir is equipped by a safety/relief valve (1.5 bar abs.) and underpressure valve (0.7 bar abs.) and its input and output are blocked by a solenoid valve in order to control the pressure and volume flow of the oxidizing agent into a fuel cell. In the reach of the oxidizing agent, mass flow-meter (approx. 120 NL/min max.) and humidifier follow in order to saturate the oxidizing agent by water vapors. Water leaving the humidifier is downtaken into a product water reservoir (tank). From there, water passes through humidifiers and is discharged into the sewerage, or it is further used.

3.5 Cooling air circuit control

The cooling air is suctioned by a radial fan from the surrounding environment into a cooling circle. The cooling air passes through the filter of mechanical impurities and radial fan into a mass flow-meter equipped by a sensor of temperature and pressure (approx. 500 NL/min max.), from where it is further driven to cooling channels inside bipolar plates of a fuel cell. The exit from the fuel cell cooling air is equipped by temperature sensors. The heated cooling air is driven to hydrogen reservoirs.

4. Control of a vehicle powered by a fuel cell

The vehicle powered by hydrogen fuel cell needs an electronic control system assuring operation of its different parts. The complex electronic control is necessary already for basic

operation of the vehicle, because there are a lot of subsystems that have to be coordinated and controlled. The control system assures especially following tasks:

Control of fuel cell operation – a hydrogen input valve control, a combustion products output valve control, a fuel cell fan control, coupling of produced electrical energy to an electric DC-drive system.

Control of DC-drive system – motor current control, speed control.

Processing security tasks – assuring safe operation of a fuel cell system and a drive system, processing of hydrogen detector information, temperature measuring.

Managing the driver control panel – complete interface to pilot that allows controlling the car – start/stop, speed set point, time measuring, emergency buttons and indicators.

Creating data archives with saved process variables – saving important process data to archives that can be then exported and analyzed.

Sending actual data to display panel in car – display panel in the car is the “process” visualization of the system. All important data are online displayed on it.

Communication with a PC monitoring station – control system send data and receive commands from the PC monitoring station using wireless communication system.

4.1 Basic fuel cell control

A basic fuel cell control concerns in a proper fuel cell operation in its all activity phases. For this task, most usually an electronic control system is used. The control system provides particularly (see Fig 6):

Safe start of the cell activity – fuel cell start is a sequence of activities which should be made for the cell to be transferred to a status when it supplies the electric power. This particularly means to supply the reaction air (Place 2, Fig. 6) and reaction hydrogen (Place 4, Fig. 6) into the whole volume of the fuel cell. After achieving some cell voltage level, the system enters a stage of the electric power production.

Proper cell functioning in the stage when it supplies the power to the appliance – in this stage, the cell supplies electric power to the appliance (Place 6, Fig. 6). In a point of the cell control, practically no control actions are required, a basic control system task is to monitor statuses of important variables – fuel cell voltage and current, temperature, and potentially also other ones. Based on these variables, it can be assessed whether the cell is loaded regularly or whether it is overloaded and, therefore, there is a risk of its damage.

Safe fuel cell switch-off – a process of a fuel cell switch-off contains again several actions which put the cell into a not active status. This particularly means shutting off the reaction hydrogen inlet and consumption of reaction gases which were left in the fuel cell volume (Place 8, Fig. 6). The consumption of these reaction gases will take place when the hydrogen inlet is closed however an appliance is still connected. Under such conditions, the residual hydrogen is consumed from the cell volume, and, simultaneously, cell voltage drops. In case of the voltage drop below some limit, the appliance can be disconnected, and the cell enters a state when it is switched off. In the Place 6, Fig. 6, a situation can occur when the cell should be immediately shut off as well as the appliance should be immediately disconnected (status 9, Fig. 6). This can be done however the residual hydrogen inside the fuel cell can cause membrane damage. Therefore, the described switching off method is only suitable to apply in critical situations (e.g. when hydrogen escape is detected) and still, however, it is suitable to provide reaction gases use or removal from the cell volume.

Reaction to non-standard situations (safety functions) – this particularly means states related to the fuel cell operation which could result into system safety decrease or to its damage. This particularly means cell overheating, hydrogen escape, reaction gas pressure increase, etc.

4.2 Electric drive control

The electric drive of a car with a fuel cell is the main consumer of electric power supplied by the fuel cell. The drive control has a critical influence on the car power consumption. Two basic conceptions are applied for fuel cell driven vehicles:

A conception when a fuel cell supplies the power into some power system of a vehicle as e.g. a battery or a super capacitor. Applying this conception, a fuel cell can run in the optimal regime and need not necessarily to respond immediately to load demands. A vehicle power system designed in this way can draw the power also from other sources, it can apply power recuperation, etc.

A conception when a fuel cell supplies the power directly into the electric drive system of the vehicle. In this design, it should immediately respond to load demands. The drive unit should be controlled so that the power takeoff from the cell is sufficiently continuous and smooth and the cell is not overloaded.

A way of the drive control depends on its type. It can be a DC motor, a motor with electronic commutation, a synchronous motor, etc. A motor type should be chosen according to required properties of a vehicle. The drive usually needs to use an electronic control system. This control system can be a part of the control system for a fuel cell, or it can be a separate system.

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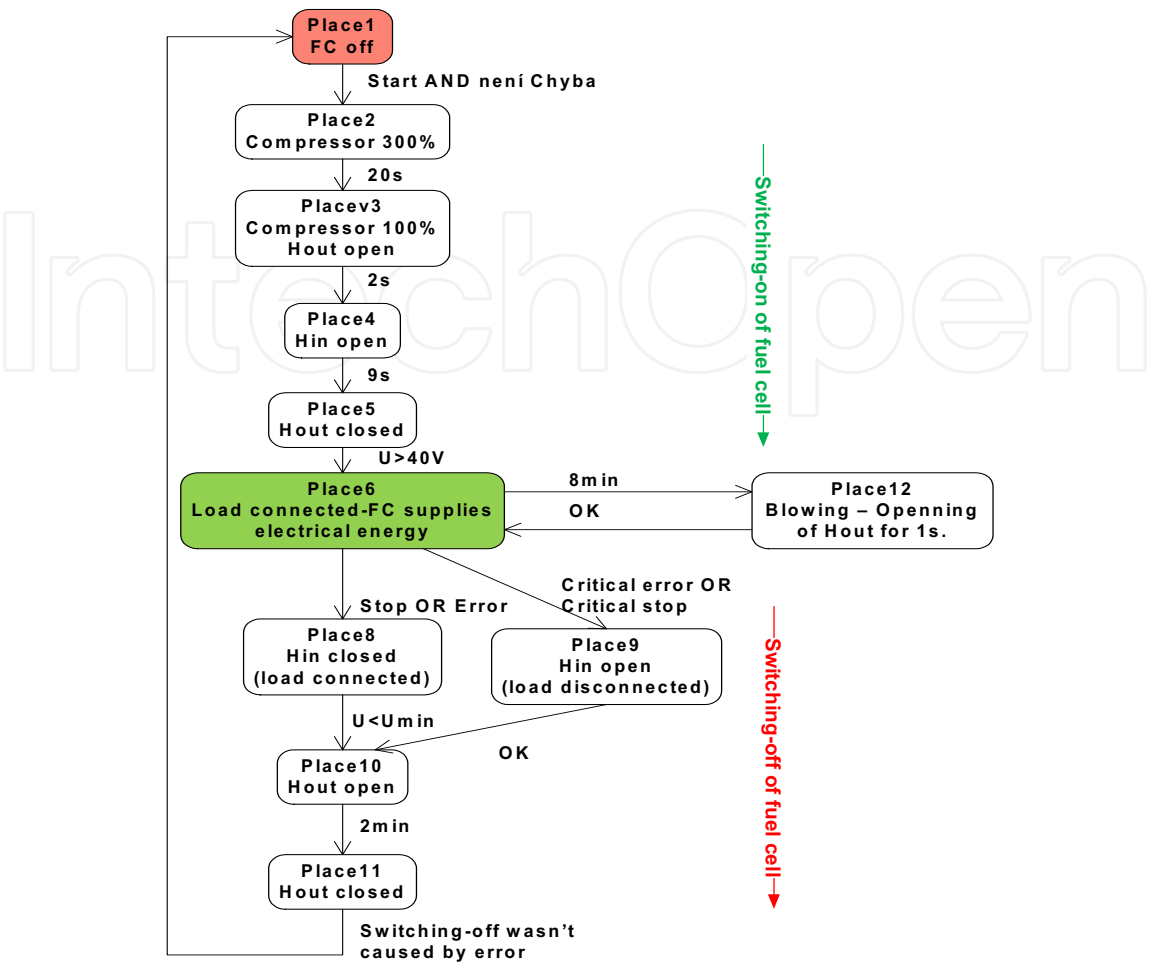


Fig. 6. Basic fuel cell control.

4.3 User-pilot interface

A fuel cell vehicle should be equipped by a user interface which enables a driver to control the vehicle. The complexity of this user interface depends on a vehicle character, however, it should contain at least primary control elements and indicators for the fuel cell system control:

- Controller for the fuel cell switching on and off.
- Controller for setting a required vehicle speed.

Vehicle status indicators – of a character of display or set of indicators regarding the fuel cell condition, operation mode, defects and faults, speed, speed, electrical variables, etc.

5. An example of a real application

A team of several specialists and students of Department of Measurement and Control, VSB-Technical University of Ostrava has designed and realized a prototype of hydrogen powered car based on fuel cell technology and electrical DC drive. The car was realized according to rules of Shell Eco-Marathon competition which is focused on economization of

energy in mobile vehicles. The project is called HydrogenIX (Fig. 7), development and testing activities were realized between 2005 and today.

The project is closely related with the educational process and motivation of students for further research activity in the form of construction of a mobile system driven by electrical motor and fed from electrochemical generator with the fuel cell.

By the HydrogenIX project and related technical and technological problems, the team tries to involve the students of bachelor, master and doctoral degree on Faculty of Mechanical Engineering and Faculty of Electrical Engineering and Computer Science to problems of non-traditional power sources and their applications.

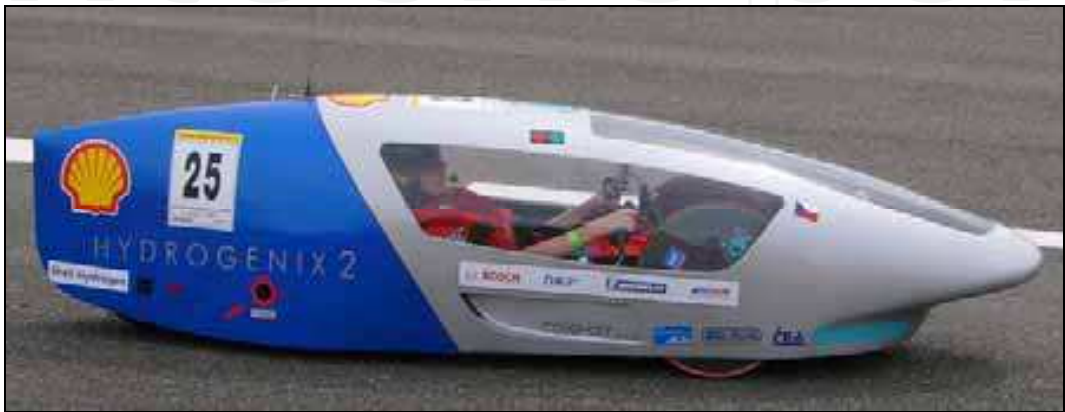


Fig. 7. The HydrogenIX car.

Car parameters:

- Aerodynamic shape of the car body.
- Power of the fuel cell – 1.2 kW.
- 2 DC motor of 150W.

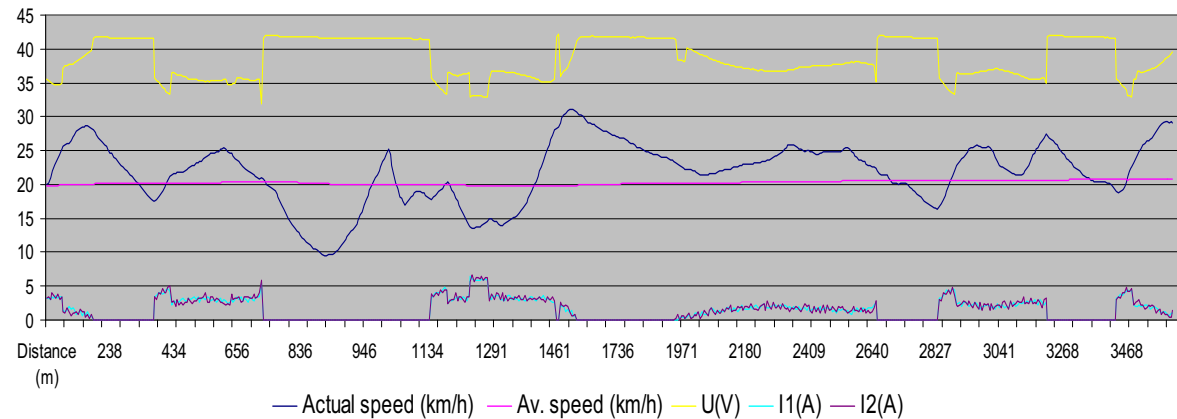


Fig. 8. A record of data of a run at the race circuit in Nogaro, France.

7. Conclusion

The top perspective is provided by an electromotor drive with a current source from a fuel cell which transfers the power contained in the fuel (hydrogen or hydrocarbon) directly to electric power. Currently, long-term verification testing has been taking place. This comprises verification of prototypes for a purpose of introduction of series and mass production. A principal fuel cell problem is represented by development of an electrolyte meeting the criteria of mass production, performance efficiency, service life and price.

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This book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of contemporary robotics and autonomous systems. The volume is organized in four thematic parts according to the main subjects, regarding the recent advances in the contemporary robotics. The first thematic topics of the book are devoted to the theoretical issues. This includes development of algorithms for automatic trajectory generation using redundancy resolution scheme, intelligent algorithms for robotic grasping, modelling approach for reactive mode handling of flexible manufacturing and design of an advanced controller for robot manipulators. The second part of the book deals with different aspects of robot calibration and sensing. This includes a geometric and threshold calibration of a multiple robotic line-vision system, robot-based inline 2D/3D quality monitoring using picture-taking and laser triangulation, and a study on prospective polymer composite materials for flexible tactile sensors. The third part addresses issues of mobile robots and multi-agent systems, including SLAM of mobile robots based on fusion of odometry and visual data, configuration of a localization system by a team of mobile robots, development of generic real-time motion controller for differential mobile robots, control of fuel cells of mobile robots, modelling of omni-directional wheeled-based robots, building of hunter- hybrid tracking environment, as well as design of a cooperative control in distributed population-based multi-agent approach. The fourth part presents recent approaches and results in humanoid and bioinspirative robotics. It deals with design of adaptive control of anthropomorphic biped gait, building of dynamic-based simulation for humanoid robot walking, building controller for perceptual motor control dynamics of humans and biomimetic approach to control mechatronic structure using smart materials.

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