Fuel Cells and Fuel Cell Power Supply Systems – an Overwiev

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Abstract – **In this paper general review of the fuel cell as an alternative power supply is given. Fuel cell is an electrochemical power source where internal combustion phase of the fuel is omittted and overall efficiency is two to three times higer compared to conventional power supplies. Fuel cell operation principle, types, advantages and disatvantages are described. At the end a power conditioning subsystem wiith its components is analysed.**

Keywords – **Electrochemical power source, Fuel cell, Alternative power supply, Fuel cell power supply systems.**

I. INTRODUCTION

At the beginning of the 21at sentury, fuell cells meet the power needs of variety of applications. The fuel cell (FC) is an electrochemical device that converts the chemical energy into electrical and thermal energy through direct conversion process. The basic features of a FC system are composed of six basic subsystems: a fuel cell stack, a fuel processor, an air, water and thermal management, and power conditioner systems (PCS). The overall system promises to provide a number of advantages, such as diversity of fuels (natural gas, methanol, etc.), high efficiency at full and part load, compatibility of wide range of sizes, and indpendence of environmental pollution [1] – [3].

Fuel cells as energy source has been present since 1839. They were discovered and developed by the english physicist Willliam Grove. But, since then, for more over one century they were not more than a laboratory curiosity [4]. After the period of 120 years since the fuel cells emerged, NASA demonstrated some of their potential aplications in the space flights exploration. Consequently, the industry has started recognizing the commercial aspects of the fuel cells, which due to the technological barriers and their high production costs were not economically profitable at that stage of technology. [5].

However since the midst of the 80's of the 20th century, Office of Transportation Technologies at the U.S. Depatment of Energy, has started to support fuel cells technology which has aroused the interest of over 100 companies worldwide to support the R&D of the fuel cells, implementation and economic payoff .

The most common application areas of fuel cell can be classified in five main groups as shown in fig.1 [6].

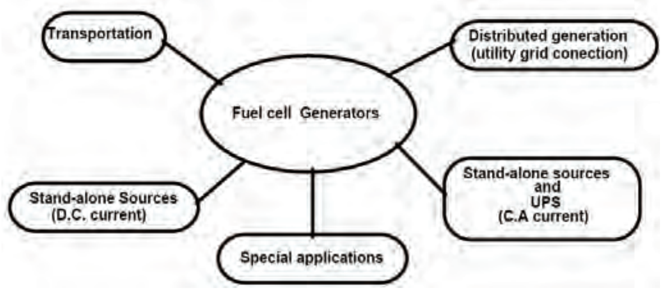

Fig. 1 Classification of fuel cell application

II. DESCRIPTION AND OPERATIONAL PRINCIPLE OF THE FUEL CELLS

The fuel cell is a mini power source generating electrical energy without the combustion stage. The basic physical structure of the fuel cell is consisted of an electrolyte layer (membrane) which in contact with the two porous electrodes (anode and cathode) on its both sides [7]. Porosity of the electrodes enhace the active electrode area hundreds, even thousand times. This fact is very important because electrochemical reactions take palce on the electrode surface. Catalyst is incorporated in the elctrode microstructure. e.g., platinum, nickel or their alloys which accelerate the speed of electrode's electrochemical reactions [7]. The chemical energy is directly transformed into electrical energy and heat when the hydrogen fuel reacts with the oxygen from the air [4], [5]. Water is the sole byproduct of the reaction. The basic electrochemical reaction is the following one [8]:

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (1)

Cathode reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (2)

Overall reaction: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$ (3)

Looking at the the previous equations, one can get a wrong impression that this process is very simple, but actually the physical and chemical processes happening on each of the electrodes and membrane are rather complex. A schematic fuel cell representation with flow directions of the fuel, reactant and ion current is given in the Fig. 2 [2].

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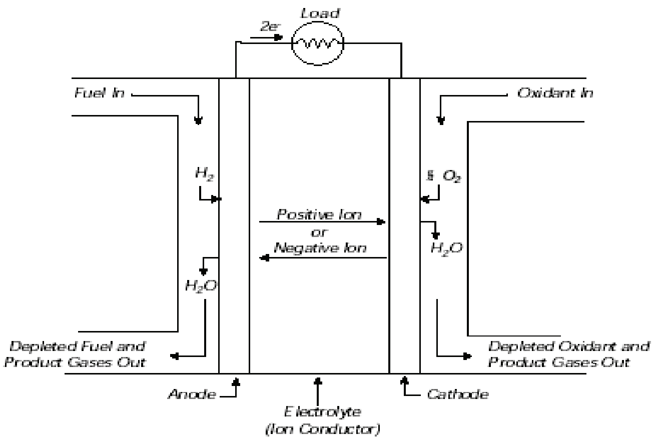


Fig 2.Operational principle of the fuel cell

Single fuel cell at no load (e.g. polymere electrolyte fuel cell - PEFC) in ideal case, generates voltage of 1,16 V at the temperature of 80 °C and gas pressure of 1 bar. Loaded fuel cell at this operational conditions generates 0,7 V. Thereby 60% of the fuel energy is transformed into electrical energy [4]. Maximum emf, E, gained during the hydrogen and air reaction ($H_2 + ½O_2 \rightarrow H_2O$) at the specified values of temperature and pressure can be determined by the following expression:

$$E = -\frac{\Delta G}{nF} \qquad (4)$$

where ΔG is Gibbs free energy, n is number of electrons participating in the reaction, and F is the Faraday constant.

In order to use the fuel cell as energy source practically, a number of single fuel cell has to be serially connected (stacked) to gain the higher output voltage.

When the hydrogen is used as a fuel, the pollutants are not products of the reaction. Hydrogen fuel could be produced by electrolysis process using renewable power sources as sun, hydro, geothermal and wind energy. But the hydrogen could be extracted from any hydrocarbons e.g. petrol, naphta, biomass, natural and LPG, methanol, ethanol, etc.

The most often classification of the fuel cell is according to the type of the used electrolyte [7]. So there are five types of fuel cell although basically the same electrochemical reaction takes place in all of them [7]:

- Alkaline Fuel Cell - AFC: AFC operating at 250 °C has an electrolyte of highly concentrated potassium hydroxide KOH while those operating at lower temperatures (120 °C) have lowly concentrated KOH. The electrolyte is retained in an asbestos matrix. Wide spectrum of catalysts is used: Ni, Ag etc. The fuel is limited to non-reactive constituents except for hydrogen.
- Polymer Electrolyte Membrane Fuel Cell - PEMFC: Electrolyte in this fuel cell is ionic membrane (Sulfuric acid polymer) which is excellent ionic conductor. Water is the only liquid in the PEMFC and consequently the problem with the corrosion of PEMFC elements are minimal. Water management is a key factor for PEMFC efficient operation. During the operation the PEMFC the humidity of the membrane is critical which determines the operational temperature of the PEMFC in the range of 60-100 °C. The fuel is hydrogen H_2 enriched gas with no presence of CO (fuel cell poison at low temperatures). Platinum is used as a catalyst
- Phosphoric Acid Fuel Cell - PAFC: Concentrated phosphoric acid (up to100%) is used in PAFC at operating temperatures in the range of 150 - 250 °C. At lower temperatures, phosphoric acid is bad ionic conductor, and catalyst (Pt) poisoning with CO becomes extremely severe. The relative stability of the phosphoric acid is high compared to the other acids, and that is the reason why this acid is operative at high temperatures with small water quantity which make the water management easy. Electrolyte is put up in silicon matrix while the type of the used catalyst is Pt.
- Molten Carbonate Fuel Cell - MCFC: MCFC's electrolyte is combination of alkali carbonates or combination of Na and K, placed in a ceramic matrix made up of $LiALO_2$. Operational temperature of the MCFC is in the range of 600 °C to 700 °C at which the alakali carbonates form highly ionian conductive molten salt. Ni (anode) and nickel oxide (cathode) are used to promote reaction.
- Solid Oxide Fuel Cell - SOFC: The memebrane electrolyte is solid nonporous metalic oxide usually Y_2O_3 - stabilized ZrO_2. Operational temperature is in the range from 650 to 1000 °C where ionic conduction of oxygen ions occurs. Typically anode is made of Co-ZrO_2 or Ni-ZrO_2 cermet and cathode is Sr-doped $LaMnO_3$.

Initial use of the fuel cells was in the NASA's space flights, for power generation and production of fresh water for the astronauts. Today the fuel cells might be used in three categories of aplications: transport, stationary and portable aplications.

AFC is the first modern type of fuel cell developed in the 1960's for the "Apollo" space program. The excellent performances of AFC comparing to the other types of fuel cells, are due to the active O_2 electrode kinetics and its flexibility to use a wide range of elctrocatalysts. But, pure H_2 has to be used as fuel because CO_2 in any reformed fuel reacts with KOH electrolyte to form carbonate thus reducing the electrolyte's ion mobility. Purification of the fuel is rather expensive and because of that the use of AFC is limited to the space applications where fuel is pure hydrogen. In the NASA's Space shuttle three 12 kW units have been used for 87 missions with 65 000 hourd flight time duration.

PEMFC are used in the transport aplications. Exceptionally interesting for this kind of applications is the Direct Methanol Fuel Cell - DMFC. In this type of fuel cell metilacohol (methanol) is directly used as a fuel needing no reformer stage [4]. PEMFC generate electrical energy with high efficiency and power density (180 - 250 mW/cm2) [7]. Also, this type of fuel cells can be used in a small stationary applications for generation of electrical power and heating in the individual houses. The power range is from 2 to 10 kW. This achievement is made by the cost reduction of the materials and manufacturing. Their main advantage is low operating temeperatures 60-100 °C and solid electrolyte. Due to the low operational temperature anode catalyst poisoning with CO is significant especially at higher current densities. In this case the output voltage of the fuel cell becomes unstable and fluctuating. Also due to the low operating temperatures, expensive catalysts have to be used for increasing the speed of the electrochemical reactions (platinum).

PAFC are for the time being the only one commercialized type of the fuel cell. It is relatively simple, reliable and quiet power source with 60% efficiency (with cogeneration). As fuel could be used natural gas. 60 MW of this type fuel cells generators are installed worldwide. The power range of the most of the power stations is between 50 and 200 kW, but also they are constructed in the range between 1 and 5 MW. Operational temperature is around 200 °C, and power density reaches values of 310 mW/cm^2. The PAFC anode is very sensitive to catalyst poisoning even if very small concentrations of contaminants (CO, COS and H_2S) are present. Compromise between the demand for high power density and good operational performances through the life spans of the PAFC should be made. One of the primary targets for the future PAFC development is the extension of the PAFC's life span up to 40 000 hours.

MCFC operates at around 600 °C. At this temperature many of the disadvantages of the lower as well as higher temperature cells can be alleviated with the fact that, for manufacturing MCFC, commonly available materials can be used (utilization of metal sheets reduces fabrication costs), while nickel catalyst is used instead of expensive precious metals. Reforming process takes place within the cell and CO is used directly as a fuel. However, the electrolyte in the MCFC is very corrosive and mobile while the higher temperature influences the mechanical stability and the lifetime of the MCFC materials. An Energy Research Corporation (ERC) in USA has tested a 2MW power supply which operates from 1996 in Santa Clara, Ca.

SOFC electrolyte is solid and cell can be made in tubular, planar or monolithic shape. The solid ceramic construction of the cell alleviates hardware corrosion problems characterized by the liquid electrolyte cells and is impervious to gas cross-over from one electrode to the other. The absence of liquid also eliminates the problem of electrolyte movement and flooding the electrodes. The kinetics is fast while CO is directly usable fuel as in MCFC. Also, as in MCFC, there is no requirement for CO_2 at the cathode. Operational temperature is around 1000 °C which means that the fuel is directly reformed within the cell. Disadvantages of the high operational temperature are the influences on the cell's material properties meaning the different thermal expansion mismatches. Currently two plants (25 kW and 100 kW), produced by Siemens Westinghouse Power Corporation, are installed and they both have cumulative operating time of 9500 hours. The eventual SOFC market is for large stationary fuel cell power supply systems (100 to 300 MW) using natural gas or coal as a fuel.

III. FUEL CELL POWER SUPPLY SYSTEMS

Although fuel cells generate power, power supply system based on fuel cells is a very complex system due to the fact that besides pure hydrogen, fuel cell can operate on diverse conventional fuels generating DC output power. There are many components incorporated in the fuel cell power system in order to enable processing of the fuel and to couple the power supply system to AC distributive network (power grid) as well as utilization of the generated heat in cogeneration to achieve high efficiency. In general the power supply system consists of: fuel processor or reformer, fuel cell and power supply conditioning subsystem.

In the reformer, hydrogen is extracted from the hydrocarbons by a hydrocarbons steam reforming. CO and CO_2 appear as by-products. The further treatment of CO with steam under high pressure converts it in CO_2.

Fig. 3 shows a simplified diagram of fuel cell power supply system [4]:

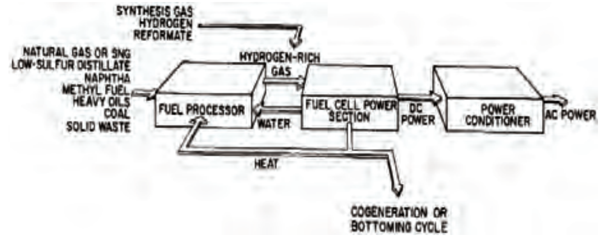


Fig 3. Fuel cell Power Supply System

The quality of the electrical power generated by a fuel cell power supply system is evaluated acoording to the following three characteristcs: efficiency, reliability and quality.

One of the main reasons for the utilization of the fuel cell as power supply is its electrical efficiency (40-57%), and with cogeneration the overall efficiency is even higher (80-85%) [9]. The measured electrical efficiency is the ratio of generated electrical energy and the energy of the fuel used in the fuel cell power supply system. Losses in all the subsystems and the interaction among them influnce on the overall efficiency of the power supply system. In order to gain and maintain the high efficiency high level of the coordination among the subsystems is required. The fast respones of the power conditioner has the key role in maintaing the high efficiency due to the step load variations.

Reliability is the second key factor in the development of the fuel cell power supply systems. They do not require complex and frequent maintenance. As alternative power supply sources they can substitute the traditional power supply systems in applications such as:

1. **Remote sites applications**, e.g. mobile telephony base stations, where service visit and investment costs for power grid construction are rather expensive,
2. **Critical power supply systems**, e.g. banks and internet servers, where power supply failures could be very expensive.

System's reliability as well as the efficiency is function of the combined subsystem's reliability.

The quality of the generated electrical power is also very important factor influencing the accpetance of the fuel cell power supply systems on the market. High quality of the electrical power demands the shape of the sinusode of the generated voltage to be close to he shape of ideal sinusoide with a constant frequency and rated value of AC voltage. This characteristcs is very essential for the proper operation of the electrical and electronic devices.

The main role of the power conditioner subsystem is to process and control the generated DC power from multiple DC sources and further to generate high quality and reliable AC power maintaining the high efficiency of the power supply system. The AC output of the system should have possibility to interact and to be synchronized with other AC generators including the power grid. [10]. The power conditioner subsystem should comply to the new standard IEEE 1547 referring to the coupling to the power grid and anti-islanding protection.

Usually the power conditioner (Fig. 4 [8]) is composed of two coupled converters: DC-DC converter and AC-DC converter and backup power supply: battery or ultra capacitors. DC-DC converter decouples and isolates the fuel cell and the DC-AC converter and step-up the low output DC voltage of the fuel cell (usually the output voltage of the serially connected fuel cell's is 48 VDC, because the connection of the fuel cells to achieve high voltages, >400 VDC, is complicated related to the reliable functioning of the fuel cell stack [4]). DC-AC converter generates stable and rated AC voltage. The battery serves as a backup during the load transients because the fuel cell dynamics is slower than the converters dynamics, and it enables starting of the fuel cell power supply system.

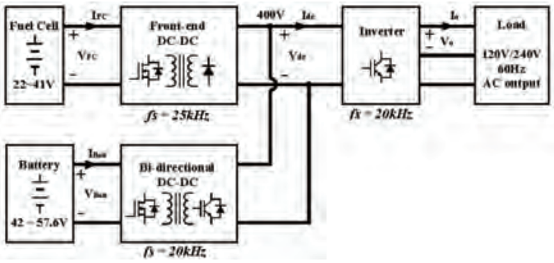
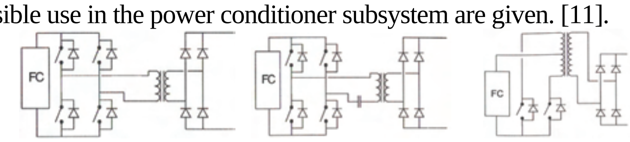


Fig 4. Power conditioner subsustem

DC-DC converter is usually put up between the fuel cell stack DC-AC converter. Different topologies for the DC-DC converter design can be used: classical high frequency hard switching topologies and resonant topologies. Bridge, half-bridge and push-pull topologies may be chosen. The advantage of resonant topologies related to the hard switching converters is avoiding the switchig losses but the design and control complexity is greatly increased. Fig. 4 shows different topologies of DC-DC converters for possible use in the power conditioner subsystem are given. [11].

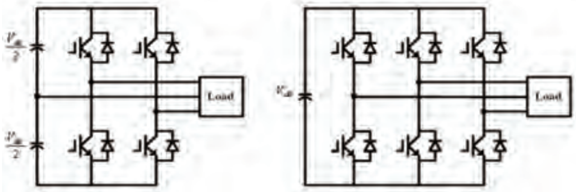


(a) (b) (c)

Fig 4. a) bridge, b) serial resonant, c) push-pull converter

DC-AC converter should generate stable and rated AC output voltage. Standard high frequency voltage mode, resonant and resonant with DC link inverters can be used. Some of the considerd topologies are given in Fig. 5 [6].

The role of the battery system that is used to prevent voltage transients during the dynamic load variations influences considerably on the topology configuration of the power conditioner subsystem. Most usually the following two methods of the battery connection in the subsystem: 1) the battery is connected on the low DC voltage side or 2) on the high DC voltage side (400 VDC). Both methods have their advantages and drawbacks [6].



(a) (b)

Fig 5. a) Four switch inverter, b) Six switch inverter

IV. CONCLUSION

The use of fuel cells as a power source in stationary and transport applications is the technology of the future. Highly developed countries, especially USA make great investments in R&D of the fuel cell's technology, production and implementation and power supply systems based on them. For this purpose, for fiscal year 2000, The American Congress provided 117 million USD in fuel cell funding through the Departments of Energy, Transportation and the Environmental Protection Agency. One of the main goals is to decrease the production costs from 3000$/kW to 1500$/kW (for cogeneration units) in order to achieve wider commercialization of the fuel cells systems. [5]. Also one of the goals is decreasing the power conditioners subsystems production costs on the value of 40$/kW [6].

Replacement of the conventional power sources with the new alternative technologies is inevitable in the near future due to the following reasons: 1) depletion of the fossil fuel reserves, especially oil and reduction of its use as a primary power source, 2) reduction of the greenhouse gases and air pollutants in transport and 3) direct influence on the deceleration of the global climate changes.

Application of the fuel cells power systems for the remote telecommunication and critical sites would influence directly on the reduction of the maintenance costs and in the near future on the investment costs for the power grid infrastructure, and indirectly on the global level regarding the previously mentioned three global factors.

Sometimes, instead of connecting in series several fuel cells to obtain the higher output voltage than one cell can give, it may be cheaper and less complex to build a low voltage DC-DC converter and to convert the low voltage of a single cell to some higher levels. Some possibilities using switched capacitor converter are analyzed in [12].

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