PEM FUEL CELLS MODELING AND THEIR USE IN A DC DISTRIBUTION SYSTEM

GECAN C.O.*, CHINDRIŞ M.**, POP G.V.*, BINDIU R.*,
VASILIU R.*, GHEORGHE D.*
*Ph.D. Student Calin.GECAN@eps.utcluj.ro, Mircea.CHINDRIS@eps.utcluj.ro,
Gabriel.POP@eps.utcluj.ro, **Professor Technical University of Cluj – Napoca 15 C. Daicoviciu St., RO 400020, Cluj – Napoca Tel: +40264 401408

Abstract: The context of the new worldwide energy policy imposes measures to produce electricity using renewable energy sources. Among these renewable sources, Fuel Cells are considered as one of the most promising devices for standalone/grid connected distributed generations (DGs) due to its cleanliness, modularity and higher potential capability. In this perspective the paper presents a PEM Fuel Cell model and the influence of different model parameters on the Fuel Cell performances. The influence of parameters such as resistance, temperature, mass-transport parameters, exchange current density and internal current density is presented in graphical representation.
The operation of Fuel Cells as a power supplying sources enables the use of direct current. Today the connection between Fuel Cell and the alternative current network is realized through a dc/ac conversion process. By using a direct current network and connection as a direct interface for those sources the dc/ac conversion process is avoided and the overall performance is increased.
To deliver the desired amount of energy, the Fuel Cells can be combined in stacks yielding higher voltage and higher currents. Some Fuel Cell Stacks promoted by different producers are presented in terms of power ratings and voltage magnitude.

Key words: PEM Fuel Cell model, parameters influences, Fuel Cell Stacks, dc connection

1. INTRODUCTION

Recent developments in power electronics components enable the use of power electronics in Low Voltage (LV) networks. The nowadays existing loads are different in many aspects from the old ones; 100 years ago, consumers were mainly represented by resistive loads and electric machines. Now the scenario is completely changed because of the influences of electronic equipment and their requirements in terms of the electric power supply. Most of the electronic equipments used today can be supplied in dc current.

On the other hand, applications of direct current occurred as a result of development and growth in importance for techniques used for obtaining electricity using renewable sources.

In the context of the new worldwide energy policy, which imposes measures to produce electricity using renewable energy sources a Low Voltage DC Network can interconnect different distributed generation units.

The number of alternative generation sources connected to the distribution system increases. Some of them, produce DC voltage, and can be easily connected to a DC distribution system directly, or through a DC/DC converter.

Photovoltaic Modules and Fuel Cells produce DC voltage outputs, and they are connected to the AC networks through power conditioning units such as DC/AC inverters. In case of a DC network the DC/AC conversion step would be avoided. Others electric energy generators using renewable sources like wind turbines are generating high-frequency AC voltage witch has to be synchronized to the AC network. In this purpose, the energy produced by the wind turbines is improved by using two conversion steps: an AC/DC conversion followed by a DC/AC conversion. An AC/DC converter may be used to avoid this expensive solution and, in this way, a connection with a DC network can be established.

A diagram of a LVDC (Low Voltage Direct Current) network witch interconnects distributed and local generation units are shown in Figure 1.

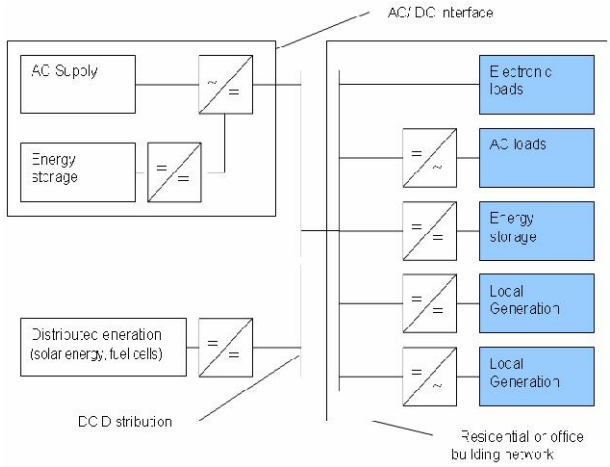

Fig 1. LVDC Network with distributed generation [1]

2. GENERAL ASPECTS REGARDING FUEL CELLS

In 1874, in his book, Mysterious Island, Jules Verne said: *"I believe that water will one day be employed as a fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light"*.

The portion of the above quote in which Jules Verne describes the joining of hydrogen and oxygen to provide a source of heat and light is a remarkably accurate description of one of the most promising new technologies now nearing commercial reality – the Fuel Cell. However, he didn't get it quite right since more energy is needed to dissociate water into hydrogen and oxygen than can be recovered so water itself cannot be considered a fuel.

The recent increasing in developing and commercializing Fuel Cells is due to its several advantages. These include "clean" by-products (e.g., water when operated on pure hydrogen), which means it is "zero emission" with extremely low (if any) emission of oxides of nitrogen and sulfur.

They also operate quietly, not having any moving parts, even when working with extra fuel processing and supply equipment.

Furthermore, they convert chemical energy contained in a fuel (hydrogen, natural gas, methanol, gasoline, etc.) directly into electrical power. By avoiding the intermediate step of converting fuel energy first into heat, which is then used to create mechanical motion and finally electrical power, Fuel Cell efficiency is not constrained by the Carnot limits of heat engines. Fuel-to-electric power efficiencies as high as 65% are likely [2], which gives fuel cells the potential to be roughly twice as efficient as the average central power station operating today.

Finally, they can increase energy security, since different types of Fuel Cell can operate on various conventional and alternative fuels such as hydrogen, ethanol, methanol, and natural gas, and hydrogen itself can be produced by harnessing a variety of renewable energy sources; such capability can help diminishing the dependence on fossil fuels.

2.1. Fuel Cells principles

A Fuel Cell operates like a battery by converting the chemical energy from reactants into electricity, but it differs from a battery in that as long as the fuel (such as hydrogen) and an oxidant (such as oxygen) is supplied, it will produce DC electricity (plus water and heat) continuously, as shown in Figure 2.

There are many variations on the basic Fuel Cell concept, but a common configuration looks like Figure 2. A single cell consists of two porous gas diffusion electrodes (anode and cathode) separated by an electrolyte. The choice of electrolyte distinguishes one fuel cell type from another

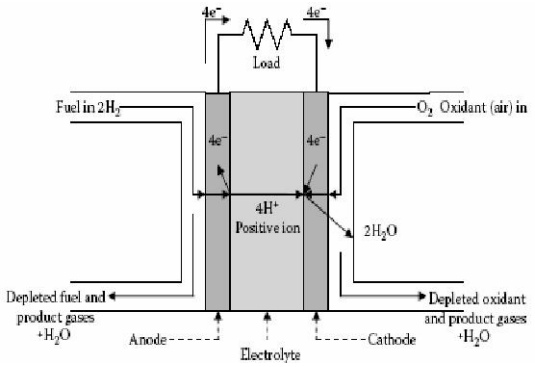

Fig. 2. PEM Fuel Cell's inputs and outputs [3]

The electrolyte consists of a thin membrane that is capable of conducting positive ions but not electrons or neutral gases. The fuel (hydrogen) is introduced on one side of the cell while an oxidizer (oxygen) enters from the opposite side. The entering hydrogen gas has a slight tendency to dissociate into protons and electrons as follows:

$$H_2 = 2H^+ + 2e^- \quad (1)$$

This dissociation can be encouraged by coating the electrodes or membrane with catalysts to help drive the reaction to the right. Since the hydrogen gas releases protons in the vicinity of the anode, there will be a concentration gradient across the membrane between the two electrodes witch will cause protons to diffuse through the membrane leaving electrons behind. As a result, the cathode takes on a positive charge with respect to the anode. Those electrons that had been left behind are drawn toward the positively charged cathode thru the external circuit since they can't pass through the membrane. The electrons will take the external circuit as a path to get to the cathode and the resulting flow of electrons that delivers energy to the load.

2.2. Fuel Cells Efficiency

The chemical energy released in a reaction can be thought of as consisting of two parts: an entropy-free part, called free energy, which can be converted directly into electrical or mechanical work, plus a part that must appear as heat. The free energy is the enthalpy created by the chemical reaction, minus the heat that must be liberated [3]. The free energy corresponds to the maximum possible, entropy free, electrical (or mechanical) output from a chemical reaction. It can be calculated as the difference between the sum of the free energies of the reactants and the products [4]:

$$\Delta G = \sum G_{prod} - \sum G_{reac} \quad (2)$$

Considering the total energy available in the process and the theoretical energy that can be converted to electrical energy, the theoretical efficiency of the fuel cell reaction is then expressed as [5]:

$$\eta_{\max} = \frac{\Delta G}{\Delta H} \quad (3)$$

The operating efficiencies of the fuel cells are lower than the theoretical values due to activation, ohmic, and mass transport over potentials.

3. PEM FUEL CELL MODELING

The free energy is the maximum possible amount of work or electricity that a Fuel Cell can deliver. Since work and electricity can be converted back and forth without loss, they are referred to as reversible forms of energy. For an ideal hydrogen fuel cell, the maximum possible electrical output is therefore equal to the magnitude free energy calculated with equation (2). The performance of a fuel cell can be expressed by the polarization curve, which describes the cell voltage - current (V - I) characteristics.

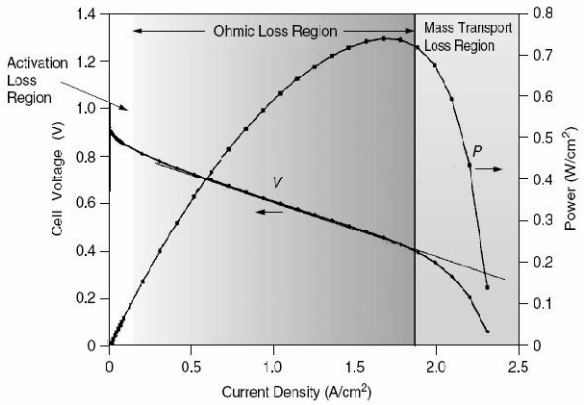

Fig. 3. The V - I and P - I curve of a real Fuel Cell [2]

Just as real heat engines don't perform nearly as well as a perfect Carnot engine, the real fuel cells don't deliver the full free energy either. As a consequence the characteristic shape of the V - I curve of a real Fuel Cell is not linear and this is due to some major losses (irreversibilities). The main sources of losses are given below [4].

3.1. Activation losses

These are caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to or from the electrode. This voltage drop is highly non-linear. Activation losses result from the energy required by the catalysts to initiate the reactions. The voltage loss due to the rate of reactions on the surface of the electrodes (V_{act}) can be computed using the Tafael equation [3,4]:

$$V_{act} = \frac{RT}{2\alpha F} \cdot \ln\left(\frac{I_{fc} + I_n}{I_0}\right) \qquad (4)$$

The constant α is called the charge transfer coefficient and is the proportion of the electrical energy applied that is harnessed in changing the rate of an electrochemical reaction. Its value depends on the reaction involved and the material the electrode is made from, but it must be in the range 0 to 1.0. For a great variety of electrode materials its value is about 0.5 [4]. At the oxygen electrode the charge transfer coefficient shows more variation, but is still between about 0.1 and 0.5 in most circumstances.

3.2. Ohmic losses and fuel crossover

The ohmic losses are represented by a voltage drop which is the straightforward resistance to the flow of electrons through the material of the electrodes and the various interconnections, as well as the resistance to the flow of ions through the electrolyte. This voltage drop is essentially proportional to current density, linear, and so is called ohmic losses, or sometimes as resistive losses.

The fuel crossover energy loss results from the waste of fuel passing through the electrolyte, and, to a lesser extent, from electron conduction through the electrolyte. The electrolyte should only transport ions through the cell. However, a certain amount of fuel diffusion and electron flow will always be possible.

The losses due to the electrical resistance of the electrodes, and the resistance to the flow of ions in the electrolyte, are the simplest to understand and to model. The size of the voltage drop is simply proportional to the current:

$$V_{ohm} = I_{fc} \cdot R_{fc} \qquad (4)$$

3.3. Mass transport or concentration losses

These result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. Concentration affects voltage, and so this type of irreversibility is sometimes called concentration loss. Because the reduction in concentration is the result of a failure to transport sufficient reactant to the electrode surface, this type of loss is also often called mass transport loss.

The voltage loss from the reduction in concentration gases or the transport of mass of oxygen and hydrogen (Vcon) can be calculated using the following equation [3,4]:

$$V_{con} = m \cdot \exp\left(n \cdot I_{fc}\right) \qquad (5)$$

3.4. PEM Fuel Cell Model

Based on the losses that occur in its operation is useful to construct an equation that brings together all these irreversibilities, and in this way the Fuel Cell voltage can be determined using equation (6):

$$V = E - V_{act} - V_{ohm} - V_{dif} \qquad (6)$$

As it can be seen from equation (6) the PEM Fuel Cell model is taking into account all the losses presented herein. In the above equation, E represents the thermodynamic potential of the cell or reversible voltage and can be computed based on Nerst equation [3]:

$$E = V_0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}\cdot\sqrt{P_{O_2}}}{P_{H_2O_c}}\right) \quad (7)$$

Usually to obtain higher power ratings Fuel Cells are connected in series and the resulting connection is called Fuel Cell Stack. In this case, for a the Fuel Cell Stack made out of N Fuel Cells the output voltage is calculated with the following equation:

$$V = N\cdot\left(E - V_{act} - V_{ohm} - V_{dif}\right) \quad (8)$$

4. MODEL PARAMETERS INFLUENCE ON FUEL CELL PERFORMANCE

Based on the PEM Fuel Cell model described by equation (6) and using MathCAD Engineering Calculation Software the influence of different model parameters on the PEM Fuell Cell performance could be determined and presented in graphical representations.

The V – I and P – I curves of a PEM Fuel Cell are presented in Figure 4.

The model parameters values used in the representation of the polarization curve V - I and the P – I curve are presented in Table 1.

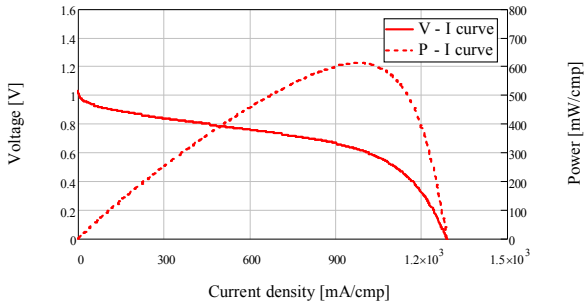

Fig. 4. The V - I and P - I curve for a PEM Fuel

Table 1. Model parameters values

Parameter	Value	UM
V_0	1.032	V
R	8.314	J/molK
T	273.15+25	K
F	96485	C/mol
P_{H2}	1.01E+5	Pa
P_{O2}	1.01E+5	Pa
P_{H2Oc}	1.01E+5	Pa
α	0.5	
I_n	2	mA/cm^2
I_0	0.1	mA/cm^2
R_{fc}	2.0E-4	kΩ•cm^2
m	2.11E-5	V
n	8E-3	cm2/mA

4.1. Fuel Cell resistance influence

To highlight how the Fuel Cell resistance influence the cell behavior and operation three values of resistances (0.2 kΩ•cm2 to 0.3 kΩ•cm2 and to 0.4 kΩ•cm2) were considered. The influence of resistance in Fuel Cell performance is presented in Figure 5.

As it can be observed from Figure 5 the Fuel Cell potential and efficiency suffer a significant increase when the resistance decreases from 0.4 kΩ•cm^2 to 0.3 kΩ•cm^2 and to 0.2 kΩ•cm^2. In consequence, it is clear that Fuel Cell with smaller resistance have higher energy potentials.

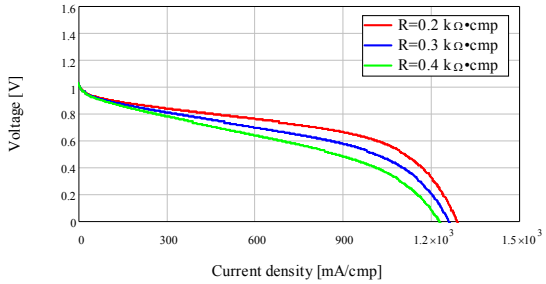

Fig. 5. Fuel Cell resistance influence on the polarization curve

4.2. Internal current density influence

Although internal currents and fuel crossover are essentially equivalent, and the fuel crossover is probably more important, the effect of these two phenomena on the cell voltage is easier to understand if it is considered only the internal current. The equivalence of the fuel crossover and the internal currents on the open circuits is an approximation, but is quite a fair one in the case of hydrogen fuel cells where the cathode activation overvoltage dominates. The importance of the internal current is much less in the case of higher temperature cells (for which the exchange current density is much higher than the internal current density) but has a important influence on low-temperature cells, such as PEM cells [4].

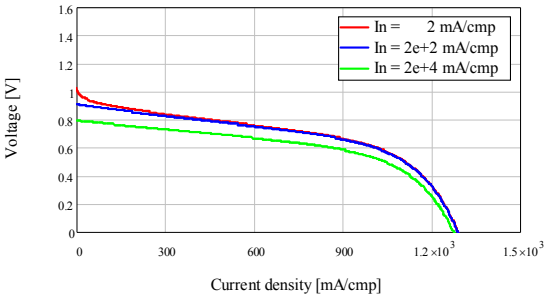

Fig. 6. Internal current density influence on the polarization curve

In low-temperature cells the internal current density causes a noticeable voltage drop at open circuit. As it can be seen in Figure 6 low values of this parameter leads to improved performance of Fuel Cells.

4.3. Exchange current density influence

The reaction at the oxygen electrode of a proton exchange membrane (PEM) or acid electrolyte fuel cell is described by equation (9):

$$O_2 + 4e^- + 4H^+ \leftrightarrow 2H_2O \quad (9)$$

At zero current density, we might suppose that there was no activity at the electrode and that this reaction does not take place. In fact this is not so; the reaction is taking place all the time and also the reverse reaction is also taking place at the same rate. Thus, there is a continual backwards and forwards flow of electrons from and to the electrolyte. This current density is the exchange current density.

Activation overpotential mainly depends on the exchange-current density for the oxygen reduction at the cathode [5]. For the case of PEM Fuel Cells it can be seen from Figure 7 that as a result of the increase of the exchange current density for the oxygen reduction reaction from 0.1 to 1 and 10 mA/cm^2, there are parallel displacements of the polarization curves, but the displacements are not so large because of the semi-logarithmic dependence of the cell potential on the exchange current density.

This exchange current density is crucial in controlling the performance of a fuel cell electrode. It is vital to make its value as high as possible.

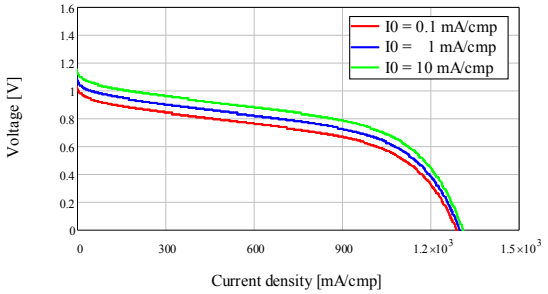

Fig. 7. Exchange current density influence on the polarization curve

The appearance of the T parameter in equation (4) might give the impression that raising the temperature increases the overvoltage. In fact this is very rarely the case, as the effect of temperature increases the exchange current density and consequently the overall effect is to reduce the activation overvoltage. By reducing the activation overpotential the Fuel Cell performance is improved. Another reason for the improved performances is that higher temperatures improve mass transfer within the fuel cells and result in a net decrease in cell resistance: as the temperature increases the electronic conduction in metals decreases but the ionic conduction in the electrolyte increases [6].

4.4. Mass-Transport Parameters influence

In the semi-empirical equation (5), the two parameters *m* and *n* account for the mass-transport phenomena in PEM Fuel Cells. This term describes the third region of the polarization curve, where the cell potential departs from the linear region and falls exponentially because of mass transport limitations.

The dependence of cell efficiency on m is linear, while that on n is exponential. Hence, the effect of n is more pronounced in the V – I curve than the effect of m.

This can be verified by examining Figures 8 and 9. In Figure 8, the increase of m from 2x10^{-5} V to 3x10^{-5} V and 4x10^{-5} V causes a decrease in the cell efficiency. The intermediate ohmic region is not affected by the change in m.

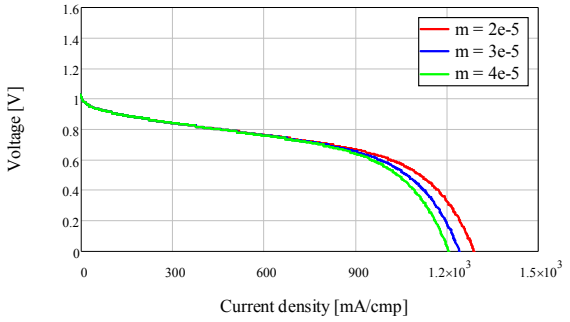

Fig. 8. Mass transport parameter m influence on the polarization curve

On the contrary, by changing the value of n from 8x10^{-3} cm^2/mA to 7x10^{-3} cm^2/mA and to 6x10^{-3} cm^2/mA, the fuel cell performance is dramatically affected in the high current density region, with a higher loss in cell efficiency, both in the mass transport and ohmic region

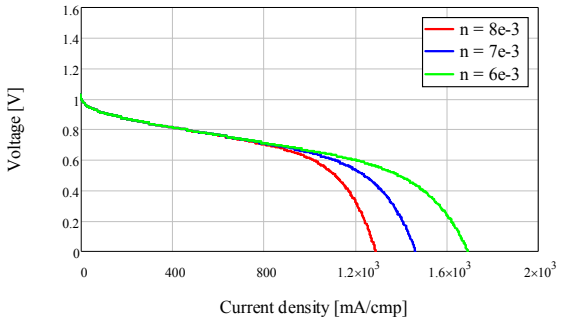

Fig. 9. Mass transport parameter n influence on the polarization curve

From Figure 8 and 9 is obvious that both mass-transport parameters will determine a decreasing Fuel Cell efficiency with an increase of m and n. The initial part of the polarization curve remains unchanged for the mass-transport parameters variation. The effect is noticeable on the second part of the ohmic region and mass-transport region and is more pronounced in the case of n parameter, because of its stronger effect on the diffusion phenomena.

5. FUEL CELLS IN A DC DISTRIBUTION SYSTEM

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yields higher voltage, and parallel allows a higher current to be supplied. Such a design is called a Fuel Cell Stack. Further, the cell surface area can be increased, to allow stronger current from each cell.

Fuel Cell have a high degree of application in the transport industry, being widely used today for electric cars, buses, scooters, boats, airplanes. In addition the Fuel

Cell Stack can also be used as backup sources for telecommunications systems. The technical information of a 3-5 kW Fuel Cell Stack which can be used as a back-up supply source is presented in Figure 10.

Power Rating	5 kW or 3 kW
Nominal Voltage	48 Vdc or 24 Vdc
Voltage Adjustable	48 to 52 Vdc, 24 to 26 Vdc
Size (W x D x H)	1.5 x 1.1 x 1.9 m (60 x 43 x 77 in)
Weight (Product)	726 kg (1,600 lbs)
Fuel Specification	HydroPlus (methanol/water)
Fuel Tank	210 L (55 gal)
Ambient Temperature	-40°C to +50°C (-40°F to 122°F)*
Location	Outdoor Rated
Elevation	0 to 2000 m (0 to 6562 ft)**
Communications	4 Dry Contacts (relays), Ethernet, and Wireless Modem (GPRS)
Certifications	CE and ANSI/CSA FC-1
Typical Run Time Standard 55 Gal Tank	120 Hours @ 2 kW Output Power 48 Hours @ 5 kW Output Power

Fig. 10. 5 kW Fuel Cell Stack P = 3 – 5 KW, U = 24/48 V dc [7]

Research in this area has enabled the appearance on the market of Fuel Cell Stacks that can be integrated as local sources in a distribution system. Some companies are producing Stacks that can be used in stationary applications. An example of a 5 kW Fuel Cell Stack is presented in Figure 11.

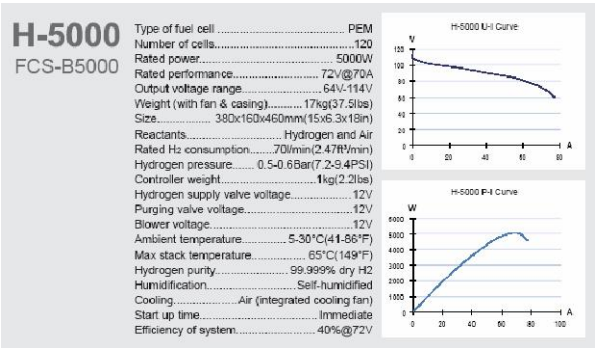

Fig. 11. 5 kW Fuel Cell Stack P = 5 KW, U = 64/114 V dc [7]

The Fuel Cell technology progressed quickly and today some producers like [8] can provide energy supplying local solutions based on Fuel Cells. These local generation stations can be achieved with different power ratings depending on application:

- 300 kW: food/beverage processing plants, manufacturing facilities, hotels, hospitals, universities, and utilities;
- 1400 kW: wastewater treatment, manufacturing, large hotels, hospitals and universities;
- 2800 kW: hospitals, universities, manufacturing facilities, wastewater treatment plants, and grid support.

The operation of Fuel Cells as a power supplying sources enables the use of direct current. Today the connection between Fuel Cell and the alternative current network is realized through a dc/ac conversion process. By using a direct current network and connection as a direct interface the dc/ac conversion process can be avoided and the overall performance increased. The connection with the ac distribution system can be realized directly or thru a dc-dc converter as presented in Figure 12.

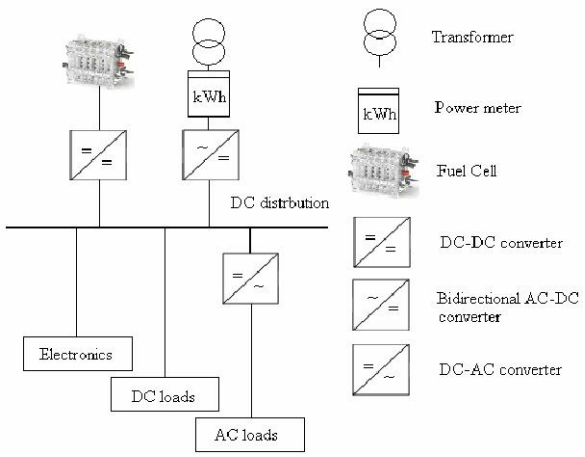

Fig. 12. Fuel Cell in a DC distribution system

CONCLUSIONS

Petroleum, natural gas, and coal are the three main types of fossil fuels that all have their drawbacks. Fuel Cells provide a source of energy in the form of electricity and even if this technology is still expensive it is clear that Fuel Cells represent a solution for energy supply in the near future.

In this paper the PEM Fuell Cell performance was investigated taking into consideration the different model parameters variations.

Using MathCAD Engineering Calculation Software and the PEM Fuel Cell model presented, the influence of the model parameters on the cell performance could be determined and presented thru graphical representations. Analyzing the polarization curves obtained for different values of the investigated parameters some observations could be made:

- to improve the efficiency the Fuel Cell resistance has to be as small as possible;
- lower values of the internal current density and higher values of exchange current density will improve the Fuel Cell efficiency;
- the increase of both m and n parameters will cause a decrease of the Fuel Cell efficiency (a more significant influence on the cell performance has the n parameter).

Besides a PEM Fuel Cell model, the paper presents also the technical information of some Fuel Cells Stacks in respect of power ratings, voltage output and applications fields.

NOMENCLATURE

ΔG	change in Gibbs free energy, [J/mol];
ΔH	change in enthalpy, [J/mol];
η_{max}	cell maximum possible efficiency;
E	thermodynamic potential of the cell, [V];
V_{act}	activation overvoltage, [V];
V_{ohm}	ohmic overvoltage, [V];

V_{conc} concentration overvoltage, [V];
R universal gas constant, [J/mol-K];
T cell operating temperature, [k];
α constant associated with cell activation losses ;
F Faraday's constant, [C/mol];
I_{fc} cell output current, [mA/cm^2];
I_n cell internal current density, [A/cm^2];
I_0 cell exchange current density, [A/cm^2];
R_{fc} area specific resistance, [kΩ•cm^2];
m constant in the mass transfer voltage, [V];
n constant in the mass transfer voltage, [cm^2/mA];
V_0 open-cell voltage, [V];
P_{H2} partial pressure of hydrogen inside cell anode, [Pa];
P_{O2} partial pressure of oxygen inside cell cathode, [Pa];
P_{H2Oc} partial pressure of water vapor inside cell cathode, [Pa];
N number of cells in series.

REFERENCES

[1]. G. Postiglione, "DC Distribution System for Home and Office", M. Sc. Thesis, Chalmers University of Technology, Goteborg, Sweden, 2001
[2]. G. M., Masters, Renewable and Efficient Electric Power Systems, Editura John Wiley & Sons, SUA, 2004, ISBN 0-471-28060-7.
[3]. B., Gou, W.K., Na, ş.a, "Fuel Cells Modeling, Control, and Applications", CRC Press, SUA, 2009, ISBN 978-1-4200-7161-0.
[4]. J., Larminie, A., Dicks, Fuel Cell Systems Explained, Editura Wiley, SUA, 2002, ISBN 978-0-470-84857-9.
[5]. S. Srinivasan, Fuel Cells from Fundamentals to Applications, Springer Science - Business Media, USA, 2006, ISBN 978-0387-25116-5
[6]. S. Al-Baghdadi, S. Al-Janabi, "Optimization Study of Proton Exchange Membrane Fuel Cell Performance", Turkish J. Eng. Env. Sci., 2005, pp. 235 - 240.
[7]. ***Horizon Fuel Cell Technologies Pte. Ltd., www.horizonfuelcell.com
[8]. ***FuelCell Energy Inc., www.fuelcellenergy.com