Paper No. T7-1.2, pp. 1-5

15th INTERNATIONAL SYMPOSIUM on
POWER ELECTRONICS - Ee 2009
XV Međunarodni simpozijum Energetska elektronika – Ee 2009
NOVI SAD, REPUBLIC OF SERBIA, October 28th - 30th, 2009

DESIGN OF A PEM FUEL CELL SIMULATOR BASED ON DC-DC BUCK CONVERTER*

Georgi Georgievski, Goce L. Arsov
SS Cyril and Methodius University, Faculty of Electrical Engineering and Information Technologies, Skopje, Republic of Macedonia

Abstract: *Modeling of fuel cells is getting more and more important as power fuel cell stacks being available and have to be integrated into real power systems. This paper presents a novel circuit simulator for a PEM fuel cell that can be used to design fuel cell based systems. The simulator is consisted of a DC-DC buck converter driven by PIC 16F877 microcontroller. The proposed circuit can be used in design and analysis of fuel cell power systems.*

Key Words: ***PEM Fuel cell, Modeling, Design, Simulation, Pulse Width Modulation (PWM)***

1. INTRODUCTION

Fuel cells as energy source have been present since 1839. They were discovered and developed by the English physicist William Grove. But, since then, for more over one century they were not more than a laboratory curiosity [1]. After the period of 120 years since the fuel cells emerged, NASA demonstrated some of their potential applications 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 [2]. Today, fuel cells of various types have emerged as promising alternative sources of "clean energy" for applications ranging from automotive industry to residential and commercial installations. This has created a need for a class of specialized power converters geared to interface between the fuel cell device and the end–user appliance, often as a battery charger. Specifications for power conversion equipment depend on the fuel cell's physical properties and manufacturing economics. The cells' output voltage is dependent on the load. So, there is a need to model the fuel cell for optimizing its performance and also for developing fuel cell power converters for various applications.

The proton exchange membrane fuel cell (PEMFC) has been considered as a promising kind of fuel cell during the last 20 years because of its low working temperature, compactness, and easy and safe operational modes. The proton exchange membrane (PEM) fuel cell is very simple and uses a polymer (membrane) as the solid electrolyte and a platinum catalyst.

It is possible, during the design process, to avoid use of very expensive fuel cells by using electric circuit which would be able to simulate the characteristics of a real fuel cell. Such simulator circuit can simulate characteristics of different fuel cells only by changing the parameters which control the operation of the circuit.

Up to now different type of models of PEM fuel cell were proposed [4] - [12]. Unfortunately, most of the proposed models cannot be used for practical realization of a fuel cell simulator.

In this paper the design of PEM Fuel Cell simulator based on DC-DC buck converter [3] digitally controlled by PIC 16F877 microcontroller is presented. Such fuel cell simulator can be used in preliminary design of fuel cell based systems.

2. FUEL CELL CHARACTERISTICS [13]-[15]

The fuel cell directly converts chemical energy into electrical energy. The chemical energy released from the fuel cell can be calculated from the change in Gibbs free energy (Δ_{gf}) which is the difference between the Gibbs free energy of the product and the Gibbs free energy of the reactants [14]. The Gibbs free energy is used to represent the available energy to do external work. For the hydrogen/oxygen fuel cell, the overall chemical reaction can be expressed as:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1}$$

and the change in the Gibbs free energy as:

$$\Delta g_f = (g_f)_{H_2O} - (g_f)_{H_2} - (g_f)_{O_2} \tag{2}$$

The change in Gibbs free energy varies with both temperature and pressure:

* This work is supported by the Ministry of Education and Science of Republic of Macedonia (Project No: 13-936/3-05)

$$\Delta g_f = \Delta g_f^0 - RT_{fc} \ln\left[\frac{p_{H_2} p_{O_2}}{p_{H_2O}}\right] \quad (3)$$

where Δg_f^0 is the change in Gibbs free energy in standard pressure (1 bar) which varies with temperature T_{fc} in Kelvin. The partial pressures p_{H2}, p_{O2} and p_{H2O} of the hydrogen, oxygen and vapor are expressed in *bar*. *R* is the universal gas constant, 8.31454 J/(kg·K). The value of Δg_f is negative, which means that the energy is released from the reaction.

For each mole of hydrogen, two moles of electrons pass around the external circuit and the electrical work done (charge × voltage) is:

$$W = -2FE \quad \text{(J)} \quad (4)$$

where *F* is the Faraday constant (96485 C) which represents the electric charge of one mole of electrons and *E* is the voltage of the fuel cell. The electrical work done would be equal to the change in Gibbs free energy if the system were considered reversible:

$$\Delta g_f = -2FE \quad (5)$$

The reversible open circuit voltage of the fuel cell or "Nernst" voltage of hydrogen fuel cell is:

$$E = -\frac{\Delta g_f}{2F} = \frac{\Delta g_f^0}{2F} + \frac{RT_{fc}}{2F} \ln\left[\frac{p_{H_2} p_{O_2}}{p_{H_2O}}\right] \quad (6)$$

$$E = 1.229 - 0.85 \times 10^{-3}(T_{fc} - 298.15) +$$
$$+ 4.3085 \times 10^{-3} T_{fc}\left[\ln(p_{H_2}) + \frac{1}{2}\ln(p_{O_2})\right] \quad (7)$$

T_{fc} is expressed in Kelvin, and p_{H2} and p_{O2} in atm.

The actual voltage of the fuel cell is less than the value calculated by equation (7). Typical PEM fuel cell performance plot is given in Fig.1. The differences are result of losses or irreversibilities.

The current density, cell current per cell active area A_{fc}(cm^2), is:

$$i = \frac{I_{st}}{A_{fc}} \quad (8)$$

The fuel cell losses are attributed to three categories: the *activation* loss, the *ohmic* loss and the *concentration* losses.

The voltage drop due to activation loss is dominated by the cathode reaction conditions. The relation between the activation overvoltage v_{act} and the current density is described by the Tafel equation:

$$v_{act} = a\,ln(\frac{i}{i_0}) \quad (9)$$

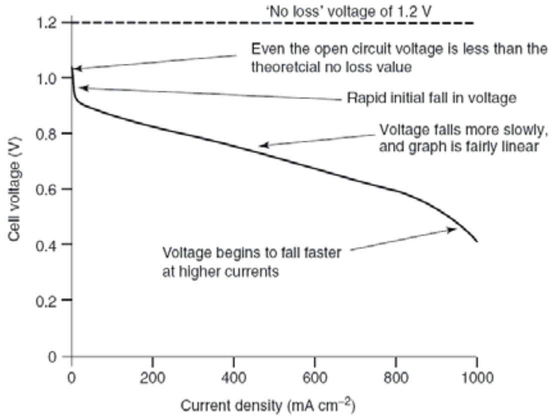


Fig. 1. *Graph showing the voltage-current dependence of a typical PEM fuel cell*

where, *a* is a constant and i_0, the exchange current density, is also a constant. Both constants can be determined empirically. For low temperature PEM fuel cell, the typical value of i_0 is about 0.1mA/cm^2.

The ohmic loss arises from the resistance of the polymer membrane to the transfer of protons and the resistance of the electrode and the collector plate to the transfer of electrons. The voltage drop that corresponds to the ohmic loss is proportional to the current density:

$$v_{ohm} = i \cdot R_{ohm} \quad (10)$$

R_{ohm} (Ω·cm^2) is the internal electrical resistance. The resistance depends strongly on the membrane humidity and the cell temperature.

The concentration loss or concentration overvoltage results from the drop in concentration of the reactants as they are consumed in the reaction. These losses are the reason for rapid voltage drop at high current densities. The voltage drop due to concentration losses is given by:

$$v_{conc} = i(c_2 \frac{i}{i_{\max}})^{C_3} \quad (11)$$

where c_2, c_3 and i_{max} are constants that depend on the temperature and the reactant partial pressure and can be determined empirically. The parameter i_{max} is the current density that causes precipitation voltage drops.

By combining all voltage drops associated with all the losses, the single fuel cell operating voltage can be expressed as:

$$v_{fc} = E - a \cdot ln(\frac{i}{i_0}) - [i \cdot R_{ohm}] - \left[i \cdot \left(c_2 \frac{i}{i_{max}}\right)^{C_3}\right] \quad (12)$$

where, the open circuit voltage *E* is given by (7).

The fuel cell stack comprises multiple fuel cells (*n*) connected in series. The stack voltage can be calculated as:

$$v_{st} = n v_{fc} \quad (13)$$

3. PEM FUEL CELL SIMULATOR DESIGN

The proposed PEM fuel cell simulator is composed of two parts: the power circuit and the control circuit. To achieve appropriate power supplied to the load the digitally controlled DC-DC buck converter [17] is proposed as a main power circuit. The control is performed by the microcontroller PIC 16F877 [18]. The microcontroller is connected in the feedback loop of the main power stage. This way, the output voltage is automatically changed in response to any change in the output current in accordance to the *V-I* polarization characteristics of any PEM fuel cells.

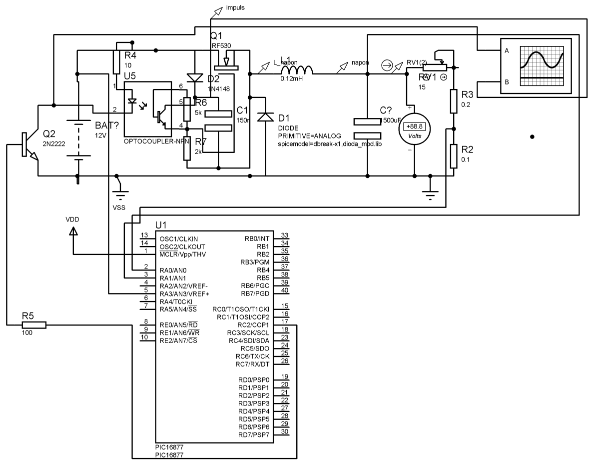


Fig. 2. *Circuit diagram of the realized DC-DC buck converter*

The complete circuit diagram realized with simulation program PROTEUS PROFESSIONAL is shown in Fig. 2.

3.1. Design of the Power part – DC-DC buck converter

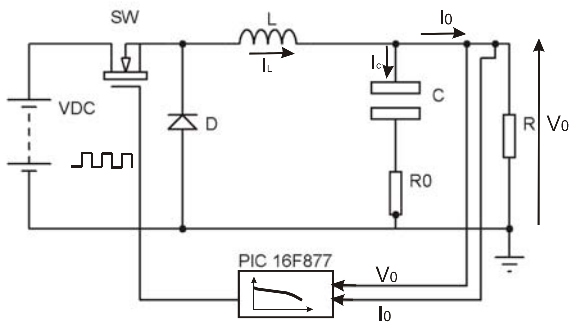


Fig. 3. *The basic circuit of the DC-DC buck converter controlled by microcontroller*

DC-DC buck converter is realized with MOS-transistor switch (SW), diode (D) and *LC* filter (inductance *L* and capacitance *C*) that are selected in the following manner (Fig. 3.).

As a main switch the MOSFET IRF 530 has been chosen. Its main characteristics are: fast switching characteristics and low on-resistance.

As a diode MUR 860 with low forward voltage drop and ultra fast reverse recovery time (t_{rr}<60ns) has been selected.

In general the output voltage of the DC-DC buck converter is independent of the switching frequency [17]. Because the *AC* losses in the DC-DC buck converter are inversely proportional to the switching period *T*, decreasing the period *T* results in decreased size of the filter elements (*L* and *C*), but increased losses in the switching transistor and, possibly, necessity to use larger heat sink to keep the switching transistor temperature within desired limits. The optimal switching frequency for this type of circuits may vary in the range of 20-50 kHz, in order to minimize the switching losses in the MOSFET. For this project it is set to 40 kHz.

The inductance *L* is chosen in the manner that it's current does not become discontinuous before the DC output current falls to its specified minimum value, which, in most cases, is one tenth the nominal value. The inductor must be designed so that it does not saturate at DC current of $1.1I_{on}$. So we have:

$$L = \frac{(V_{dc} - V_0)T_{on}}{0.2I_0} = \frac{(12-6)\cdot 25\cdot 10^{-6}}{0.2\cdot 5} = 150\mu H$$

The capacitance, *C*, determines the output voltage ripple. Because the capacitor is not an ideal one, it has parasitic inductance (L_0) and resistance (R_0) in series with its capacitance. They are characterized as equivalent series resistance (ESR) and equivalent series inductance (ESL). The influence of the series inductance can be neglected for switching frequency below 300 kHz [17]. There are two ripple components in the output voltage, one due to R_0 and second due to *C*. The ripple component due to *ESR* is proportional to the peak to peak inductor ramp current (I_2-I_1), and the ripple component due to *C* is proportional to average current value. For a capacitor selection, it is necessary to know the value of R_0 which is given by capacitor manufacturers. Over a large range of voltage ratings and capacitors values, for aluminum electrolytic capacitors, the product $R_0 \cdot C$ tends to be constant. It ranges from $(50–80)\cdot 10^{-6}$ usually. Let us assume that the resistive ripple component is V_{rr}=0.05V peak-to-peak. Then we may write: $0.05=(I_2–I_1)\cdot R_0=1\cdot R_0$ and $R_0=0.05\Omega$. For $R_0\cdot C = 50\text{x}10^{-6}$:

$$C = 50\cdot 10^{-6} / 0.05 = 1000\mu F \tag{15}$$

The capacitive ripple voltage V_{cr} is:

$$V_{cr} = \frac{I\cdot t}{C} = \frac{0.25\cdot 25\cdot 10^{-6}}{1000\cdot 10^{-6}} = 0.00625 \text{ V} \tag{16}$$

where, the average value of current is $(I_2\text{-}I_1)/4=0.25$A. Usually the capacitive ripple voltage may be neglected, because it is much smaller compared to the ripple voltage due to the resistance R_0.

3.2. Design of the control part of the DC-DC buck converter with microcontroller PIC 16F877

The microcontroller PIC 16F877 is used to control the proper work of the DC-DC buck converter. PIC 16F877 contains two 10-bit A/D convertors by which the measured analog output current and voltage values are converted to digital for further processing. The PWM module generates the driving pulses for the switching transistor in the power stage. The PEM fuel cell polarization *V-I* characteristic can be either calculated using the relations (5) – (13), obtained by using some of the referred simulation models, or measured using a real fuel cell. For simplicity, here, the measured curve of a single fuel cell, at specified conditions, is implemented in the PIC memory. The values should be modified according to the stack current and voltage capabilities and the working temperature for any particular case. In this case the basic curve is modified for simulating the 12V/5A PEM fuel cell stack.

In accordance to the PEMFC *V-I* polarization characteristic the microcontroller controls the output voltage in the relation to the output current. The control algorithm is shown in Fig. 4. The microcontroller PIC 16F877 uses a set of 35 instructions by which the control process is defined. The control program was developed using the simulation program PROTEUS PROFESSIONAL [3].

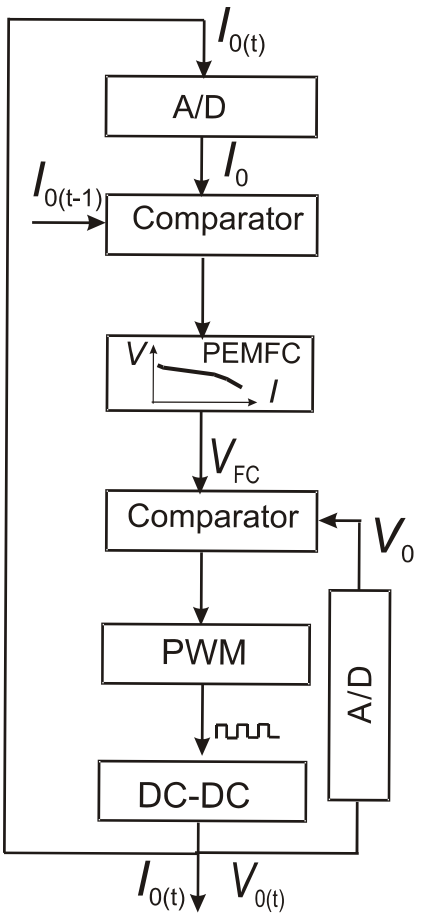


Fig. 4. *Block diagram of the control algorithm*

Since control circuit is almost always referenced to ground, it is necessary to have a gate drive circuit that allows the MOSFET to be isolated from the ground. This can be realized using either optical isolation circuits or pulse transformers. In this project the optical isolation (optocoupler 4N25) is used (Fig. 5).

When the current flows through the photo-diode the photo-transistor is turned on. Consequently, the gate to source voltage rises above the threshold value and the MOSFET is turning on.

The current is measured through the voltage drop across the 0.1Ω resistor (R_0). The voltage divider may be used to adjust the output *V-I* characteristics of the DC-DC buck converter (Fig. 6). This way, by this simulator circuit, different *V-I* characteristics may be realized in order to satisfy PEM fuel cell *V-I* characteristics for different working temperatures or pressures.

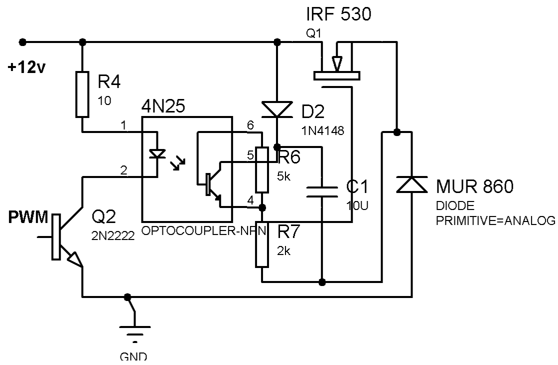


Fig. 5. *Part of driving gate circuit realized with optocoupler 4N25*

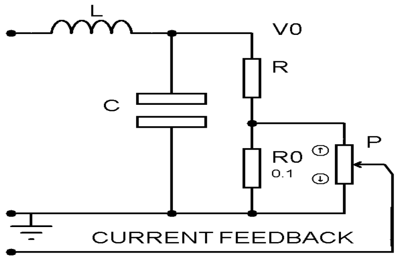
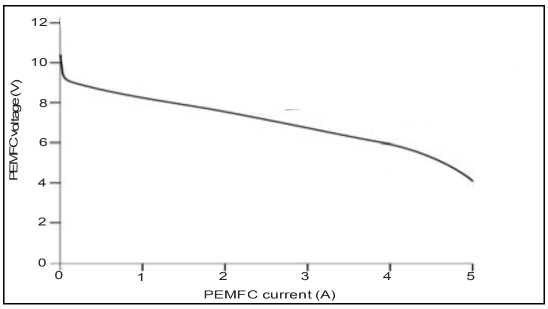


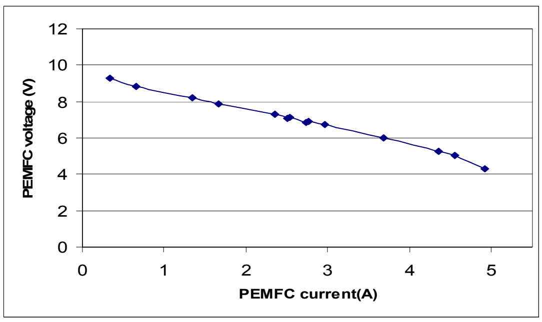
Fig. 6. *Current feedback with voltage divider*

4. RESULTS AND DISCUSSIONS

The extensive experimental investigation of the proposed simulator has been performed. Here, some experimental results for simulation of a 12V/5A PEM fuel cell are presented.



a)



b)

Fig.7. *Polarization V-I curves of a 12V/5A PEMFC:*
a) theoretical PEMFC curve,
b) experimental results for the realized PEMFC simulator

The *V-I* polarization characteristics implemented in the PIC memory was obtained by increasing the ideal stack voltage to 12 V, and the active cell area by 5 (to support the current of 5 A). These values are multiples of the initial polarization characteristics implemented in the PIC memory. This characteristic is shown in Fig. 7 a).

The microcontroller PIC 16F877 is programmed according to the block diagram given in Fig. 4.

The microcontroller PIC16F877 measures current I_0 and voltage V_0 and with the software, implemented in its memory, creates PWM pulses for driving the buck converter. The period of the PWM pulses is constant and was chosen to be 25 μs. The pulse width is controlled by the implemented polarization curve and measured values of the output current, I_0, and voltage, V_0. The output voltage varies from 12 V, at system idle, to about 5V, at rated current of 5 A. The experimentally attained *V-I* characteristics, using the proposed simulator, are shown in Fig. 7 b). It can be seen that the curves presented in Figs. 7 a) and 7 b) match very well.

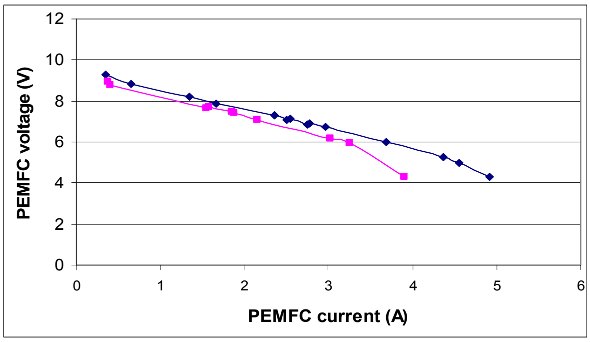


Fig.8. *Obtained V-I characteristics from the realized PEMFC simulator with the voltage divider*

Using the voltage divider in the current feedback, it is possible to obtain very quickly the *V-I* polarization characteristics for other working temperatures or pressures. An example is shown in Fig.8.

In comparison with the real PEM fuel cell dynamic characteristics, the realized simulator has very quick transient response. By suitable programming of the microcontroller PIC 16F877 it is possible to obtain similar transient response which will correspond to that of a real PEM fuel cell.

5. CONCLUSION

The design of a PEM fuel cell simulator based on digitally controlled DC-DC buck converter is presented. The proposed simulator can be easily used in design, analyses and realization of fuel cell power systems. Due to the digital nature of the control system, it is possible to make quick changes to the mathematical model, thus avoiding as much as possible changes in the system hardware.

The hardware changes may affect only the power stage, especially when larger stuck current and/or voltage have to be obtained. The temperature and pressure characteristics can be easily implemented in the proposed simulator, either by implementing them in the control algorithm or by changing the current feedback signal using voltage divider as shown in Fig. 6.

The proposed simulator can also be used to test power systems designed to interact with PEM fuel cells, in order to prevent stack degradation caused by the electric behavior of the system. The foreseen benefits of the proposed simulator are also, the ability to work without reagents in a non-specialized environment, in a reproducible way and with faster start-up/turn-off operation.

The experimental investigations performed on the 12V/5A PEM fuel cell simulator have shown very good behavior of the proposed system and good match of the simulator output characteristics with the real PEM fuel cell polarization curve.

6. ACKNOWLEDGEMENT

This work is supported by the Ministry of Education and Science of Republic of Macedonia (Project No: 13–936/3-05)

7. REFERENCES

[1] S. Thomas, M. Zalbowitz, "Fuel Cells – Green Power," *Los Alamos National Laboratory*, New Mexico, 1999.

[2] "Fuel Cells Fact Sheet", *Environmental and Energy Study Institute*, Washington DC, February 2000.

[3] G. Gjorgievski, G. L. Arsov "Preliminary Design of a PEM Fuel Cell simulator Based on DC-DC Buck Converter", *PROC INDEL 2008*, Banja Luka, 2008

[4] S. Yerramalla, A. Davari, A. Feliachi, "Dynamic modeling and analysis of polymer electrolyte fuel cell", *Proc. IEEE Power Engineering Soc. Summer Meeting*, vol. 1, 2002, pp. 82–86.

[5] J.B. van der Merwe, C. Turpin, T. Meynard, B. Lafage, "The installation, modeling and utilization of a 200W PEM fuel cell source for converter based applications", *Proc. IEEE Power Electronics Specialists Conference*, *2002*, pp. 333–338

[6] K. Dannenberg, P. Ekdunge, G. Lindbergh, "Mathematical model of the PEMFC", *J. Appl. Electrochem*. 30 (2000) pp. 1377–1387.

[7] A. Kazim, H.T. Liu, P. Forges, "Modeling of performance of PEM fuel cells with conventional and interdigitated flow fields", *J. Appl. Electrochem*. 29 (1999) pp. 1409–1416.

[8] W. Turner, M. Parten, D. Vines, J. Jones, T. Maxwell, "Modeling a PEM fuel cell for use in a hybrid electric vehicle", *Proc. IEEE Vehicular Technology Conference*, 1999, pp. 16–20.

[9] R. Gemmen, P. Famouri, "PEM fuel cell electric circuit model", Proc. of the Power Electronics for Fuel Cells Workshop, 2002.

[10] D. Yu, S. Yuvarajan, "Electronic circuit model for proton exchange membrane fuel cells", *Journal of Power Sources,* 142 (2005). pp. 238–242

[11] A. Capel, J. Calvente, R.Giral1, H. Valderrama-Blavi, A. Romero, and L. Martínez-Salamero, "Modeling of a Fuel Cell as an Energy Source Power System" *Proc SAAEI 2006*, pp 64-68

[12] G. L. Arsov, "Parametric Pspice Model of a PEM Fuel Cell" *Proc. 14th Int. Symposium on Power Electronics – Ee 2007* - CD ROM

[13] National Energy Technology Laboratory, "*Fuel Cell Hand Book*", sixth ed., 2002, pp. 2.1–2.20.

[14] Jay T. Pukrushpan, Anna G. Stefanopouplu, Huei Peng *Control of Fuel Cell Power Systems*, Springer

[15] J. Larminie, A. Dicks, "*Fuel Cell Systems Explained*", Wiley, 2003

[17] A. I. Pressman, "*Switching Power Supply Design*", McGraw-Hill 1998

[18] Microchip, *PIC16F87X Data Sheet*