An Enriched Undergraduate Research Experience based on the Simulation, Experiments, and Theory of Fuel Cells

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Abstract - **Fuel cells are one of the key enabling technologies for future hydrogen economy. Some applications for fuel cells can be found in aerospace, automobile vehicles, power generation, etc. Despite their modern high-tech aura, fuel cells actually have been known to science for more than 150 years! It is the purpose of this paper to present a brief overview of the development and technology of fuel cells with its integration to the undergraduate electrical engineering education. This work attracted undergraduate students in the area of renewable energy by bringing them to a research work with a hands-on experience, where the students had the chance to study fuel cells and the feasibility of these technologies as a substitute to traditional fossil fuels. The students had the opportunity to do simulations, experiments, and acquire theory for an enriched electrical engineering undergraduate research experience. Clearly, undergraduate research works in renewable energy are an innovative and attractive way to make students aware of contemporary issues in areas like energy, globalization, state-of–the-art technologies, and attract them to pursue graduate studies in this area.**

Index Terms – Fuel cell, Mathematical model, Mentoring, Power electronics, Renewable energy, Undergraduate research.

I. INTRODUCTION

Since 1800, when the process of using the Electricity to decompose the water into Hydrogen (H) and Oxygen (O) was described, the principle involving the fuel cell (FC) behavior had been considered as a research subject. Different advances in this area had been developed through the past century up until then. Nowadays, fuel cells appear as alternative sources of energy which offer high efficiency, excellent part load performance, lower emissions of regulated pollutants, and a wide size range [1]. In the past, fuel cell systems (FCS) were thought to be attractive for utilities, on-site cogeneration, and specialized transportation applications such as trucks and buses. However, at the time, most demonstration projects were limited to utility power applications [2]. Right now, many researchers, manufacturers, energy companies, and regulatory agencies are currently working to develop a variety of fuel cell types and to plan the infrastructure that will support these new technologies. Moreover Industry Associations like The United States Fuel Cell Council (USFCC) are making a big effort to promote the use and the commercialization of fuel cells [3]. These efforts involve the development of new materials, economical manufacturing processes, advanced equipment for supplying air and fuel, advanced power electronics for controlling the cell output, and comprehensive approaches for systems analysis and optimization.

Taking into consideration the importance of fuel cells like a strong renewable source of energy, the Department of Electrical and Computer Engineering (ECE) of the University of Puerto Rico at Mayaguez (UPRM), through the research group in renewable energy, is encouraging the undergraduate students to get involved in the research of fuel cells and other renewable sources of energy (e.g. Photovoltaic Panels, Thermoelectric Generators). Through different class projects related with circuit analysis and design, as well as simulation and circuit implementation, the students can understand and analyze the behavior of different renewable sources of energy. Also, it is important to know that part of the mission of the ECE Department is the creation of abilities in undergraduate students such as applying knowledge of mathematics, science and engineering, designing a system, component or process, formulating and solving engineering problems. This mission is in accordance with the Accreditation Board for Engineering and Technology (ABET) criteria [4].

As an example of this work, this article will show how a small class project in power electronics is useful to analyze the behavior of Proton Exchange Membrane (PEM) FC connected to DC/DC boost converter designed by an undergraduate student.

A brief discussion about historical aspects of fuel cells and theory about their operation will be shown in sections II and III. The model used to study the FC behavior is described in section IV. The simulation results and experimental results are presented in sections V and VI, while section VII describes the conclusion about the undergraduate student work.

II. HISTORICAL ASPECTS ABOUT FUEL CELLS

For the last 20 years applications for the fuel cells are mostly replacing internal combustions engines, and providing energy in power applications. However the history of the fuel cells is more than the last 20 years; actually it has more than 150 years! Though generally considered a curiosity in the 1800s, fuel cells became the subject of intense research and development during the 1900s. In 1800, British scientists William Nicholson and Anthony Carlisle had described the process of using electricity to decompose water into hydrogen and oxygen [5]. This process is named electrolysis.

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (1)$$

In 1832, Michael Faraday reported that the quantity of elements separated by passing an electrical charge through a dissolved salt was proportional to the quantity of electric charge passed through the circuit. From these experiments the two fundamental Laws of Electrolysis were derived.

TABLE I
FARADAY´S LAWS OF ELECTROLYSIS

	Faraday Laws of Electrolysis
1st	The mass of a substance produced at an electrode during electrolysis is proportional to the number of moles of electrons (the quantity of electricity) transferred at that electrode.
2nd	The number of Faradays electric charge required to discharge one mole of substance at an electrode is equal to the number of "excess" elementary charges on that ion.

William Robert Grove, however took this idea one step further or, more accurately, one step in reverse in 1838. Grove discovered that by arranging two platinum electrodes with one end of each, immersed in a container of sulfuric acid, and the other ends separately sealed in containers of oxygen and hydrogen, a constant current would flow between the electrodes. The sealed containers held water as well as the gases, and he noted that the water level rose in both tubes as the current flowed. By combining several sets of these electrodes in a series circuit, he created what he called a "gas battery"- the first fuel cell [5]. Grove is considered to be the father of the fuel cell.

$$2H_2 + O_2 \rightarrow 2H_2O + energy \qquad (2)$$

In 1889, Ludwig Mond and assistant Carl Langer described their experiments with a gas-powered battery using coal derived “Mond-gas” that attained 6 amperes per square foot (measuring the surface area of the electrode) at 0.73 volts with electrodes of thin, perforated platinum. They called their system a fuel cell.

Friedrich Wilhelm Ostwald, a founder of the field of physical chemistry, provided much of the theoretical understanding of how fuel cells operate [5], [6]. In 1893, he experimentally determined the interconnected roles of the various components of the fuel cell: electrodes, electrolyte, oxidizing and reducing agents, anions, and cations. Grove had speculated that the action in his gas battery occurred at the point of contact between electrode, gas, and electrolyte, but was at a loss to explain further. Ostwald, drawing on his pioneering work in relating physical properties and chemical reactions, solved the puzzle of Grove's gas battery. His exploration of the underlying chemistry of fuel cells laid the ground work for later fuel cell researchers [6].

Francis Thomas Bacon (1904-1992) developed the first practical hydrogen-oxygen fuel cells, which convert air and fuel directly into electricity through electrochemical processes. He began researching alkali electrolyte fuel cells in the late 1930s. In 1939, he built a cell that used nickel gauze electrodes and operated under pressure as high as 3000 psi.

During World War II, Bacon worked on developing a fuel cell that could be used in Royal Navy submarines, and in 1958 demonstrated an alkali cell using a stack of 10-inch diameter electrodes for Britain's National Research Development Corporation. Though expensive, Bacon's fuel cells proved reliable enough to attract the attention of Pratt & Whitney. The company licensed Bacon's work for the Apollo spacecraft fuel cells [6]. Interestingly, these key works were revolutionary at their time and putting today the hydrogen in good position as the next carrier of fuel useful for the economy of the world.

III. PARAMETERS TO CONSIDER IN THE STUDY OF A PEM FC BEHAVIOR.

In the previous section, important historical facts about fuel cells were mentioned as a background for undergraduate students and faculty members who are initiating their studies in this area. In the present section as a continuation of this background, technical description about fuel cells and references for further documentation will be provided.

Proton Exchange Membrane (PEM) Fuel Cells are electrochemical devices that take hydrogen and Oxygen to produce energy. Unlike a combustion reaction of hydrogen and oxygen, which only releases a large amount of thermal energy, fuel cells convert directly the chemical energy in the fuel to electricity. However several parameters related to their operation must be approached to understand their behavior. From the thermo-chemical point of view, some of the most important parameters for a PEM FC are temperature, FC active area, Hydrogen & Oxygen pressure, membrane specific resistivity, thermodynamic potential, maximum current & voltage, and minimum voltage. A complete description of the operation of a fuel cell system can be founded in [7].

PEM Fuel Cell is also known as polymer electrolyte membrane FC, it consist of a proton conducting membrane placed in the middle of two platinum impregnated porous electrodes (membrane electrode assembly MEA) as is shown in the figure 1. When Hydrogen molecules get the anode catalyst, they split into protons and free electrons. The Protons go through the membrane to the cathode and then react with the supplied oxygen and the returning electrons to produce water. The electrons pass through an external load and produce electricity [7].

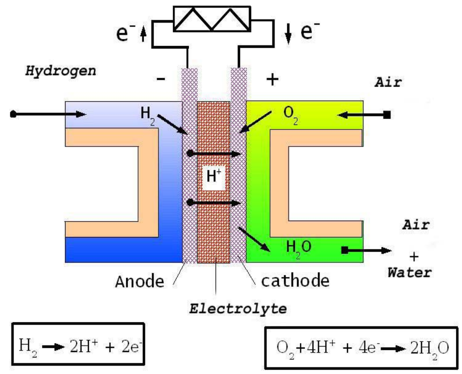

FIGURE 1
REACTION INSIDE A FUEL CELL TO PRODUCE ELECTRICITY [11]

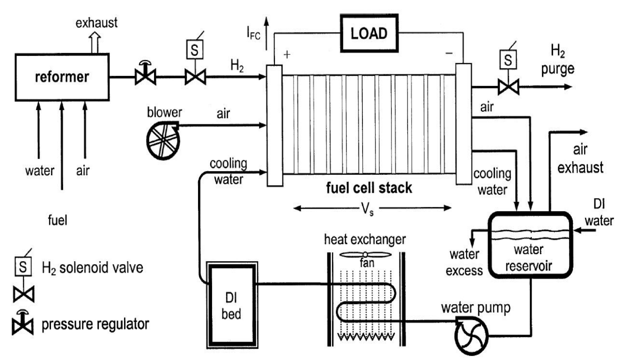

FIGURE 2
A COMPLETE FUEL CELL SYSTEM [8]

The cell voltage varies directly as a function of the system pressure as well as its current density and temperature [8]. For this reason smaller fuel cell stacks can operate at an elevated pressure and generate as much power as larger stacks operating at atmospheric pressure. To achieve this operation condition, the reactant gases of the fuel cell must be pressured to a determined value.

Another important parameter is the humidity. The humidity of the air going into the stack cathode is crucial to the low resistance of the membrane. Therefore, a humidification system must be implemented just upstream of the cathode inlet. The fuel cell system may become more complex in order to control more parameters and to raise the efficiency of the fuel cell stack. Figure 2 shows a fuel cell system.

IV. BEHAVIORAL MODEL OF A FUEL CELL

Most of the behavioral models that can be found in the literature are based on empirical models, which use many empirical parameters [9], while others are based on curve fitting experiments [10]-[11].

The model described in [11] is being studied at the UPRM. It is based only on four parameters related to the FC electrical characteristics, which makes this model very useful and easy to apply in power electronic simulations and circuit analysis.

This electrical model considers the boundary conditions and shape of the fuel cell *V-I* curve as shown in figure 3. Using this information any fuel cell can be described in terms of the values obtained by the FC *V-I* and *P-I* curves using either (3) or (4). The variables V, and I are the voltage, and current for a fuel cell with units in volts (V) and amperes (A). I_H, V_H and V_L are the high current (maximum current), high voltage (maximum voltage) and low voltage for a fuel cell. V_H can be obtained when the current is zero. V_L can be obtained when the current is I_H. The range of existence of I will be from 0 to I_H and for V will be from V_L to V_H.

$$V=V_L+(V_H-V_L)(\cos^{-1}((2I/I_H)-1)/\pi)^k \quad (3)$$

$$P=I\,V_L+I\,(V_H-V_L)(\cos^{-1}((2I/I_H)-1)/\pi)^k \quad (4)$$

The variable k is the characteristic constant for the fuel cell based on the *V-I* and *P-I* curves as described by (5). P_{max} and I_{op} are the maximum power and the optimal current, which are required to obtain the characteristic constant for a FC.

$$k=\ln((P_{max}-I_{op}V_L)/(I_{op}V_H-I_{op}V_L))\,/\,\ln(\cos^{-1}((2I_{op}/I_H)-1)/\pi) \quad (5)$$

One interesting experiment that undergraduate students can make to validate a specific model is to connect the FC to different resistive loads and to observe the variations in the voltage and current supplied by the FC. The students may register the values with different conditions depending on the FC stack or FC system used, and then plots the results. After a comparison with simulated results of the model, the students can observe and prove that the fuel cell is a non linear energy source.

The verification of the model will give to the students a stronger basis to use it in simulations and circuit analysis. As an example the behavioral model described by (3)-(5) was tested with an educational FC. In this case only the electrical characteristics of the FC are provided by the vendor, thus the model is suitable to describe the fuel cell behavior. Figure 3 and figure 4 show the measurements made by the student and its comparison with the estimated model.

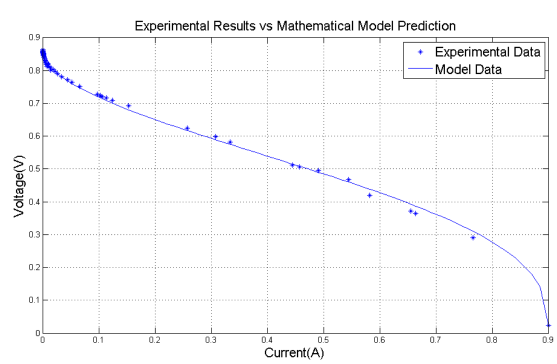

FIGURE 3
POLARIZATION CURVE, CURRENT VS VOLTAGE.

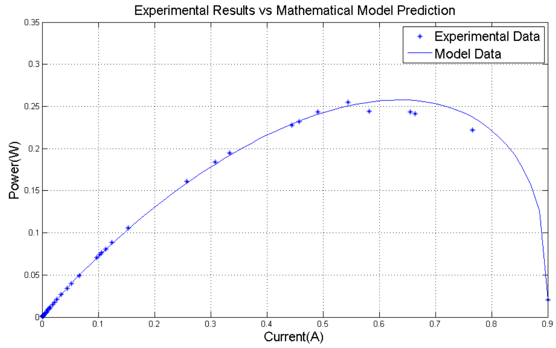

FIGURE 4
POWER CURVE, CURRENT VS POWER.

V. DC/DC BOOST CONVERTER SIMULATION USING A FC BEHAVIORAL MODEL.

DC/DC converters design is one of the principal topics in any basic course in power electronics. Undergraduate power electronic students must be able to design and implement power electronic circuits which operate under different electrical conditions, like load variations, switching element variation and power sources variations. However, only circuits with conventional DC power sources are studied in basic power electronic courses. In the following section, a DC/DC boost converter is simulated and analyzed by an undergraduate student in order to understand the behavior of the circuit when a PEM FC is connected as the input voltage as in shown in figure 6 ad figure 7. Simulations in Simulink using the Fuel Cell model in [11] are shown. Table II shows the electrical characteristic of the fuel cell that was used.

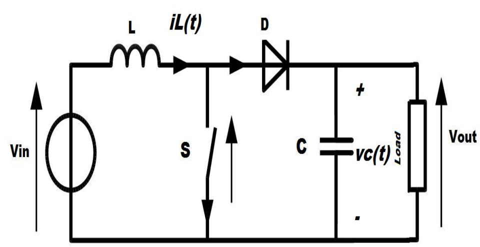

FIGURE 5
DC/DC BOOST CONVERTER

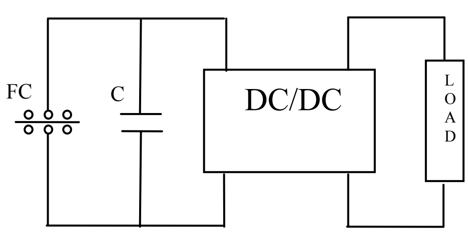

FIGURE 6
SCHEMATIC CONNECTION

For a DC/DC Boost converter (Figure 5) the average model is described by (6).

$$di_L(t)/dt = -((1-d)/L)\, v_c(t) + (1/L)V_{in}(t)$$
$$dv_c(t)/dt = ((1-d)/C)i_L(t) - (1/RC)v_c(t) \qquad (6)$$

And the output voltage (V_{out}) in terms of the input voltage (V_{in}) can be obtained by (7).

$$V_{out} = V_{in}(t)/(1-d) \qquad (7)$$

d is the PWM signal duty cycle for the switching element. The output voltage is always higher than the input voltage as the duty cycle approaches to 1.

The Boost converter was designed for a resistive load of 100 *ohms*: it was simulated for a switching frequency of 30 *kHz*. Figure 7 shows the simulated Boost converter when a fuel cell model is connected. The simulation results are shown in figure 8, when a duty cycle of 0.5 is used.

For the students, one of the main objectives of these simulations is to model non linear electrical elements using mathematical blocks in Simulink. Also the students will be able to understand the electrical characteristics of a fuel cell and how this affects the circuit behavior.

The students could observe that in comparison to conventional DC sources, the fuel cell voltage decayed from its initial value due to the connected load, and how it is expected, the output voltage at steady state in the Boost converter is twice the input fuel cell voltage when a duty cycle of 0.5 is used.

Another important factor that students could explore is the Boost converter efficiency (η). The Students may take the necessary information to calculate the power delivered by the fuel cell using the polarization curve and the power curve from the model (figure 3 and figure 4). Then after measuring the power at the boost converter output, the efficiency can be estimated.

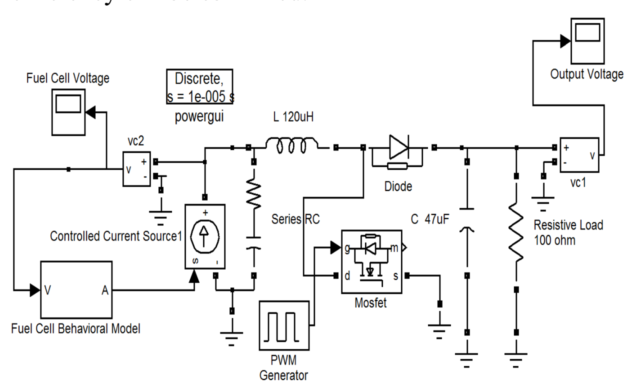

FIGURE 7
DC/DC BOOST CONVERTER IMPLEMENTED IN SIMULINK.

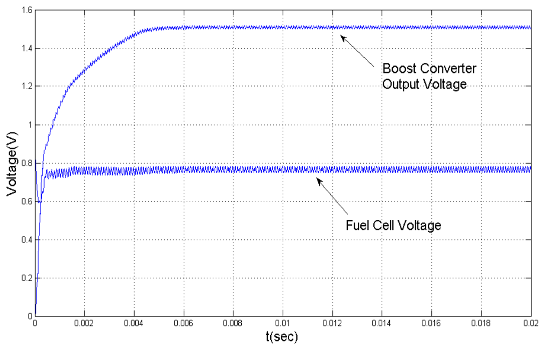

FIGURE 6
FC VOLTAGE AND OUTPUT VOLTAGE.

TABLE II
HELIOCENTRIS, FUEL CELL

Parameter	Value
Vmax (V_H)	0.860V
Imax (I_H)	0.9A
Iop	0.54A
Pmax	0.25W

VI. EXPERIMENTAL RESULTS

To implement the boost converter the student applied previous knowledge in specific areas such as electronic circuit analysis and power electronics. The first one is necessary to design the appropriate circuit to obtain the PWM and the duty cycle for the switching element activation. The second to help understand and determine the better electronic component values for the desired output voltage.

Figure 10 shows the generated PWM signal with a duty cycle of 0.5. The output Boost converter voltage (CH2) and the Input FC voltage (CH1) are shown in figure 9.

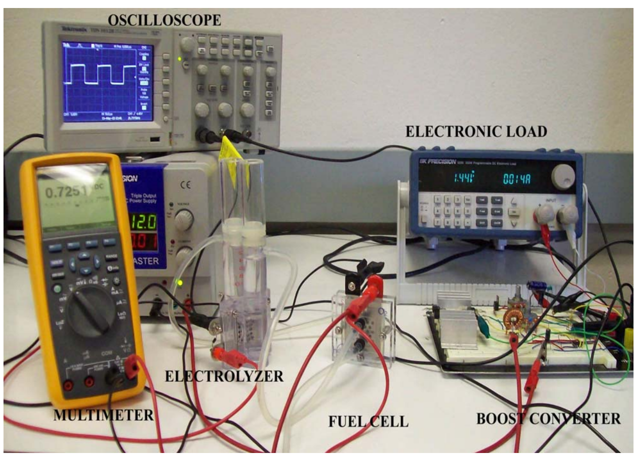

FIGURE 8
EXPERIMENT SET UP

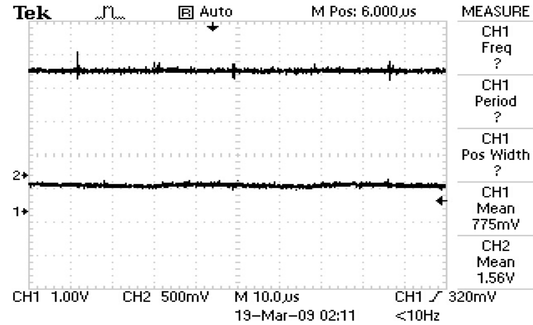

FIGURE 9
INPUT VOLTAGE AND OUTPUT VOLTAGE

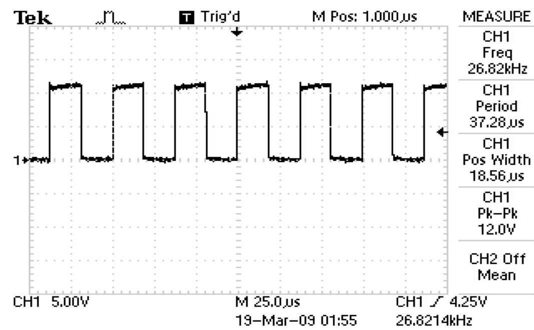

FIGURE 10
DUTY CYCLE

VII. SKILLS DEVELOPED BY THE STUDENT

This study improved the student's ability to search, understand, and discuss publications and journal articles related to FC operation and modeling.

The student could apply previous knowledge gained in the power electronic course which is given in the UPRM's curriculum. The student also acquired practice in Simulink, learning how to relate mathematical models with circuit simulation.

The experience gained by the student, serves as preparation for bigger challenges in the area of power electronics in association with the interest developed in the usage of renewable sources of energy, and its importance in the world energy sustainability. The student learned about the state of the art in fuel cells, mathematical and empirical models and the historical evolution of FC [15].

The confidence and the expertise gained by the student were important to his integral formation. The group work with graduate students helped to improve the writing and communication skills of the student, because of the follow-up made by the graduate students through the developing of writing and oral reports.

Although hydrogen considerations (i.e. consumption, concentration, pressure) were not analyzed into experimental results, the student could realize through the documentation process about the electrolysis and the experimental set up, where an electrolyzer was used to produce the hydrogen, its importance in the fuel cell performance and the different technologies used for the hydrogen supplying in different fuel cell systems.

As a synthesis of this work, a quote given by the undergraduate student involved in this project, Mr. Jose Velez is presented: “This work in the renewable energy area has been a big experience for me, where I have learned about the importance of new technologies and its role in the energy sustainability of the world. Also I have improved my abilities in circuit simulation and modeling, as well as in power electronic circuit design. I could apply in a practical way many things that I have learned in the power electronics class. Moreover, I could find many applications for the circuits that I have studied during the last semesters, which encourage me to follow in this research process for future projects related with power electronics and its application in renewable energy systems. As an example, my interest now is to find a way to extract the maximum power from the fuel cell for different loads variations.”

CONCLUSIONS

A brief discussion about the history and the importance of fuel cells has been presented. Also a simulation in Simulink of a power electronic circuit was shown using as voltage source a mathematical model for a fuel cell. The implementation of this circuit was developed using an educational PEM FC.

Although the chemical and thermodynamic parameters of the FC were unknown by the student, those were not necessary to predict the voltage and current behavior of the system.

Through a small power electronics project, the importance for an undergraduate student to get involved with the use and understanding of renewable source of energy was shown. These kinds of projects are the basis for future research of the student’s academic, life either in college or in graduate school.

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REFERENCES

[1] U.S. Department of Energy, Office of Fossil Energy, “Fuel Cell Handbook”, October 2000, cap 4.1-8.22

[2] U.S. Department of Energy, Energy Efficiency and Renewable Energy http:// www1.eere. energy. gov/ hydrogen and fuel cells

[3] U.S. Fuel Cell Council, “Fuel Cell Stimulus Plan”, http://www.usfcc.com/Fuel_Cell%20_Stimulus_12.18.08.pdf as visited on 10 March 2009

[4] The Accreditation Board for Engineering and Technology (ABET): www.abet.org.

[5] Princeton University chemistry lab website “History of Fuel Cells” http://www.princeton.edu/~chm333/2002/spring/FuelCells/fuel_cells-history.shtml as visited on 12 April 2007

[6] Smithsonian National museum of American History “Fuel Cell History Project website” http://americanhistory.si.edu/fuelcells/index.html as visited on 12 April 2007

[7] Pukrushpan,J,T; Stefanopoulou,A,G; Peng,H; “Control of Fuel Cell Breathing”, *IEEE Control Magazine*, Vol, No 24., Apr 2004, 30-46

[8] Correa, J,M; Farret, F,A; Canha, L,N; Simoes, M,G; “An electrochemical-based fuel-cell model suitable for electrical engineering automation approach”, IEEE Transactions on Industrial Electronics, Vol, No 51., Oct 2004, 1103-1112.

[9] Larmine,J,E; Dicks,A; “Fuel Systems Explained”, Wiley ,2000,. 308.

[10] Maher,A,R; Al-Baghdadi, S; “ Modelling of proton exchange membrane fuel cell performance based on semi-empirical equations”, Reneweable Energy 30, Jan 2005., 1587-1599.

[11] Ortiz-Rivera, E.I. Pan, Z. Jin Wang; “A mathematical model to describe the electrical characteristics for a fuel cell.”, *Power Electronics Specialists Conference 2008. PESC 2008. IEEE*,. 15-19 June 2008, 559-561

[12] Ortiz-Rivera, E; Rodriguez, Luis; “The Z-Source Converter as an Introduction to Power Electronics and Undergraduate Research.”, *37th ASEE/IEEE Frontiers in Education Conference., October 10-13,* T2C-5 - T2C-10.

[13] Chickamenahalli, S; Khodor, A; “ Effective Research Experience of Electrical Engineering Technology Students”, *Frontiers in Education Conference, 1998. FIE ’98. 28th Annual*, Vol 3., 4-7 Nov 1998, 1123-1126.

[14] Bjazic, T; Ban, Z; Volaric, I; “Control of a Fuel Cell Stack loaded with DC/DC boost converter”, *IEEE International Symposium* on *Industrial Electronics, 2008. ISE 2008,* 30 Jun- 2 Jul 2008.,1489-1494.

[15] Ortiz-Rivera E. I., Reyes-Hernandez A.L.; Febo, R.A. “Understanding the History of the Fuel Cells” 2007 IEEE Conference on the History of Electric Power.

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