AC 2010-2059: DESIGN OF A LABORATORY EXPERIMENT TO MEASURE FUEL CELL STACK EFFICIENCY AND LOAD RESPONSE

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Josh Goldade is originally from Velva, a small town in western North Dakota. Upon graduation from Velva High School in 2002, Josh enrolled at the University of North Dakota to major in electrical engineering. In the spring of 2005, Josh left for Sweden to study abroad for a year. After returning to the U.S., he continued on the path towards his Bachelor's degree at UND. In the summer of 2007, Josh took a six-month cooperative education position at Daktronics in Brookings, SD, and he returned to Daktronics for another summer internship in 2008. Josh graduated in December 2008, and began work on his master's degree in January 2009. During the summer of 2009 Josh took an internship with Oak Ridge National Laboratories. Josh joined the Dakota Venture Group in the fall of 2008 and currently holds the position of Vice President of Finance. Josh plans to finish his Master's of Electrical Engineering in August of 2010.

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Tessa Haagenson is from Leeds, North Dakota. She was awarded a B.S. degree in Environmental Studies from Bemidji State University in 2007, after which she spent a semester abroad as a guest graduate student in an energy studies program in Aalborg, Denmark. Tessa's additional international travel experience includes a summer study trip to Iceland through Bemidji State, a month teaching English at a summer camp in Spain, and three months in Argentina taking intensive Spanish language classes through a Rotary International program. Following seasonal employment with an environmental engineering and consulting firm in Nebraska, Tessa returned to school to supplement her academic background and pursue a career in engineering. She is currently enrolled in the electrical engineering program at the University of North Dakota and is enjoying opportunities to gain familiarity with the technical aspects of renewable energy systems.

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Hossein Salehfar received his Bachelor of Science (B.S.) degree in electrical engineering from the University of Texas at Austin, and his Master of Science (M.S.) and Doctorate (Ph.D.) degrees in electrical engineering from the Texas A&M University in College Station. He was a research assistant with the Electric Power Institute at Texas A&M University during 1985-1990. He was an Assistant Professor of Electrical Engineering at Clarkson University in New York during 1990-1995. Since 1995 he has been with the Department of Electrical Engineering at University of North Dakota, Grand Forks, where he is now a full Professor, Department Vice-Chair, and the Director of Engineering Ph.D. Programs. Dr. Salehfar has worked as a consultant for the New York Power Pool, electric utilities and coal industries in the State of North Dakota, and the North Dakota Energy and Environmental Research Center (EERC). Dr. Salehfar has very active and externally funded multidisciplinary research projects. He is currently working on a number of projects funded by the National Science Foundation (NSF), and the U.S. Department of Energy (DOE). Some of the projects that he has worked on include alternative and renewable energy systems, fuel cell technologies, power electronics, electric drives, neuro-fuzzy intelligent systems, electric power and energy systems, power systems reliability, engineering systems reliability, power systems production costing, energy and load management, and energy efficiency. He has supervised several Ph.D. and Masters level graduate students and has published his research work extensively in various journals, conferences, and books. During the past several years, Dr. Salehfar has developed and taught numerous courses at undergraduate and graduate levels including various power systems courses, alternative energy systems, electric drives, power electronics, power and other engineering systems reliability, engineering statistics, electric circuits, senior design courses, electromagnetic, control systems, signal processing, signals and systems, etc. Dr. Salehfar is an active reviewer of proposals and manuscripts for the National Science Foundation (NSF), IEEE, Power Electronics Specialist Conference (PESC) and various other international journals, conferences, and publications. He is a professional member of the

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Design of a Laboratory Experiment to Measure FC Stack Efficiency and Load Response

The University of _____ is one of a number of institutions of higher education working to train the next generation of engineers in the realm of renewable energy technology. Fuel cells are one component of this continually changing and progressing field. The importance of this technology cannot be overlooked in the overall energy production portfolio and is evidenced by their prevalence in an increasing number of industry applications. In order to ensure that engineering students graduating from the University are prepared to contribute to the continued growth of the utilization of fuel cells, efforts are being made to incorporate fuel cell education into the engineering curriculum.

The Department of Energy provided five universities with a grant to acquire fuel cell technology education tools. One of the tools acquired by The University of _____ is an Ulmer Brennstoffsellen-Manufacturing 600W Proton Exchange Membrane (PEM) fuel cell system. This fuel cell will be used to compliment the Renewable Energy Systems class with laboratory experiments. The goal is that the laboratory along with the class will provide the Junior, Senior, and Graduate level Electrical and Chemical engineering students with hands-on experience. This allows the student to supplement their classroom background with actual results. These results can then be examined through comparison with theoretical data.

This paper lays out the design and implementation of two laboratories using the 600W PEM fuel cell. The first lab illustrates how to determine the efficiency of the fuel cell stack. The knowledge gained though this lab is important for sizing fuel cell stacks to match the system into which they are integrated. The second lab will investigate the load response time of the stack. This will provide students with a better understanding of how fast fuel cells can increase or decrease their power output to match the demand of the load.

Both of these labs are designed to give students hands-on experience with applications that are very important in the world of power production. It is through these types of experiments that students gain the knowledge they need to ensure success in their future endeavors.

Introduction

A fuel cell is an electrochemical device that turns the chemical energy stored in a fuel directly into electrical energy. This renewable energy technology is gaining attention as one of the most versatile options for fulfilling electricity demands in an increasingly energy-hungry world. However, as the prevalence of alternative energy technologies like fuel cells grows, so must the number of professionals trained to work with these technologies. Thus, exposure to and understanding of fuel cells at the university level will be paramount in preparing the next generation of renewable energy engineers. This lab helps prepare those engineers by exposing them to basic characteristics of PEM fuel cells such as their efficiency and response to loading. Teaching students these basic characteristics will help them understand how fuel cells need to be sized for specific applications. Coupling the efficiency of the fuel cell with its load response shows what types of applications fuel cells can be used for.

Renewable energy engineering education at the University of _____

Several courses in renewable energy technologies are offered at the University of _____, including Methods of Hydrogen Production and Storage through the chemical engineering department, as well as an electrical engineering elective titled Renewable Energy Systems. Both are open to upper level undergraduates and graduate students in electrical and chemical engineering, and both feature fuel cell education. Furthermore, a collaborative graduate program in Sustainable Energy Engineering was recently established at the University. Each of these educational offerings could likely benefit from increased student exposure to fuel cell technology. While the research presented in this paper provides a knowledge base for future student experimentation, further development of a laboratory component for fuel cell education would provide impetus for its incorporation into the curriculum.

Additionally, the School of Engineering and Mines (SEM) at the University of _____ participates in periodic Accreditation Board of Engineering Technology (ABET) program assessments to maintain accreditation. The Board requires institutions of higher education to demonstrate that their students achieve a number of program outcomes[5]. Several of these outcomes and objectives address the need for engineers who can apply knowledge from the classroom to real-world problems. The use of hands-on experiments designed to encourage student exploration – like the laboratory activities presented in this paper – is one of the ways SEM prepares students to be successful engineers.

An introduction to proton exchange membrane fuel cells

A fuel cell consists of a positive electrode and a negative electrode, separated by an electrolyte. Direct current electricity is produced through electrochemical reactions within the cell. The fuel cell will continue to produce electrical energy as long as it is fed a steady supply of fuel and oxidant. There are several types of fuel cells, differentiated by the fuel required and the type of electrolyte. The focus of the experiment in this paper is a proton exchange membrane (PEM) type fuel cell. A PEM fuel cell uses highly purified hydrogen gas as its fuel (anode side) and oxygen from ambient air as its oxidant (cathode side). The figure below represents the flow of reactants and products in a basic fuel cell.

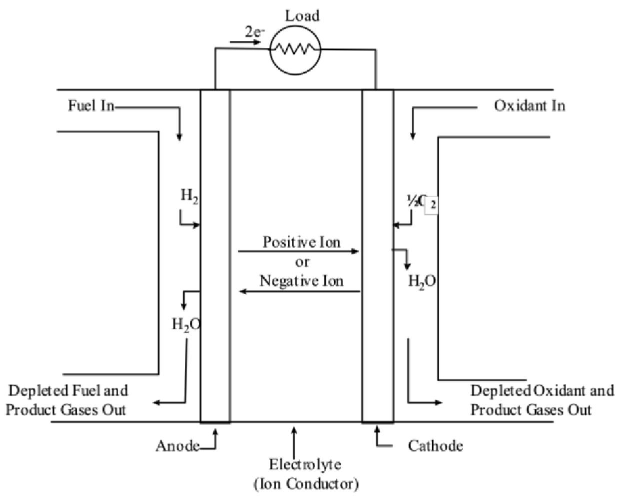

Figure 1. Individual fuel cell schematic[4]

The two electrically conductive electrodes sandwich an electrolytic layer. At the boundary of the electrolyte and either electrode, there exists a catalytic layer, typically platinum. This is where the action takes place in the cell. At one end, hydrogen splits into protons and electrons. The electrons move through the electrically conductive electrode to a current collector, then to an external load. The protons travel through the porous electrode, across the ionically conductive electrolyte to the other catalyst-electrolyte interface, where they react with oxygen as well as electrons passed from the external circuit. This produces water and heat as a by-product. The reactions that occur within the cell are described below.

Eq. 1 (Half reaction 1, at the anode):

$$H_2 \rightarrow 2H^+ + 2e^-$$

Eq. 2 (Half-reaction 2, at the cathode):

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Eq. 3 (Overall reaction):

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

Individual cells are typically combined to form a stack of cells for the purpose of providing a power output large enough for practical applications. Each individual cell has a theoretical potential of about 1.23 V [2]. The equations used to calculate the ideal voltage across the stack of cells are

Eq. 4: (Nernst equation): $V_C = V_{OC} - (RT/nF) \ln [P_p/P_R]$

where V_C is the individual cell potential after subtracting the voltage drop due to internal resistance from the ideal individual cell potential, V_{OC} is the ideal open circuit potential, R is the universal gas constant (8.313 J/K mol), T is the temperature in degrees Kelvin, n is the number of electrons required for each mole of hydrogen consumed, F is Faraday's constant (the number of Coulombs per mole of electrons, which is 96,485 C/mol) and P_p/P_R is the partial pressure of the products divided by the partial pressure of the reactants.

Eq. 5: $V_S = (N)(V_C)$

Where V_S is the stack voltage, V_C is the cell voltage , and N is the number of cells comprising the stack.

Experimental setup

The fuel cell system examined in this paper is an Ulmer Brennstoffsellen-Manufacturing 600W proton exchange membrane (PEM) fuel cell stack, with twenty-four individual cells connected in series. The system consists of the hydrogen supply, 600W fuel cell stack, cooling system, hydrogen regulator, DC/DC converter, backup battery, DC/AC inverter, and HP 600 controller. The entire system, shown with computer connected, can be seen below.

Figure 2. Ulmer Brennstoffsellen-Manufacturing 600W PEM fuel cell system and computer setup

Hydrogen is stored either as a metal hydride in a tank or as compressed gas in a separate storage tank, as shown in Figure 3, below.

Figure 3. Compressed hydrogen gas supply tank

For this experiment, compressed hydrogen gas was utilized as fuel, entering the system at approximately 15 bars (the manufacturer of the fuel cell system recommends 2 to 17 bars as an acceptable range)[8]. Oxygen is drawn into the stack from the ambient air.

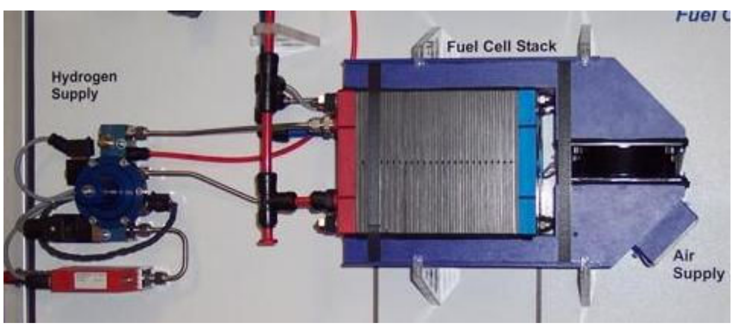

Figure 4. Close-up of the fuel cell stack and hydrogen supply control system

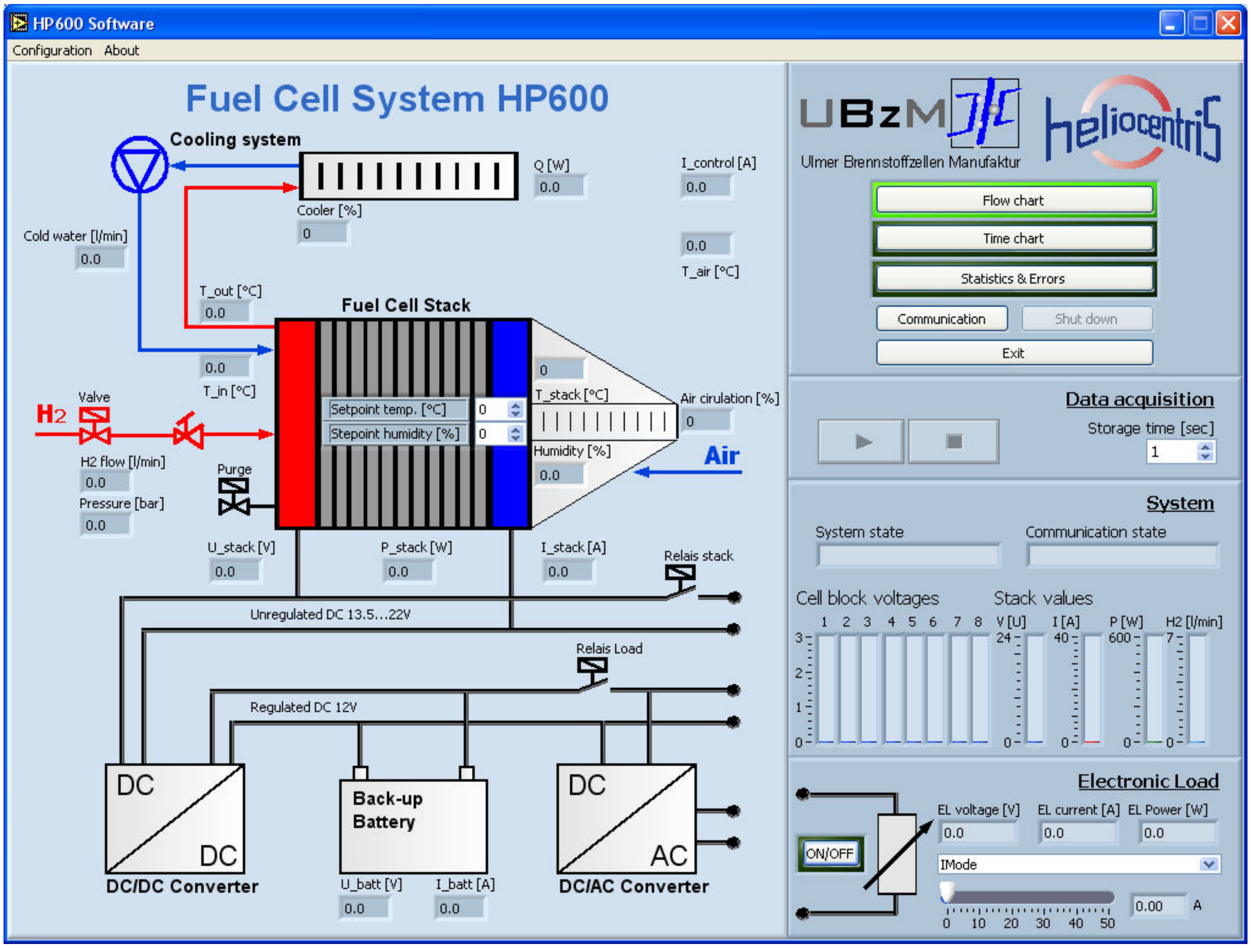

Figure 5. Data display of user interface for HP600 Fuel Cell System[8]

The HP 600 software is mostly used for monitoring the system and logging data. Most variables cannot be modified by the software but two values that can be adjusted are the set point temperature and the set point humidity.

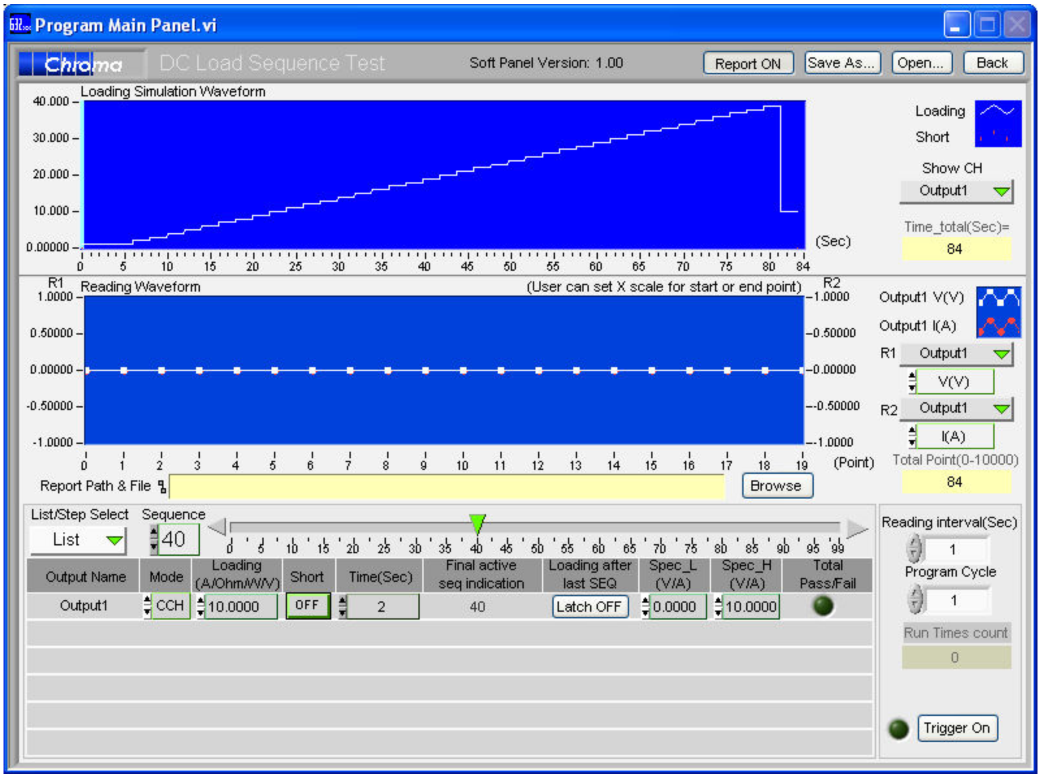

Figure 6. Data display of user interface for Chroma programmable DC load [3]

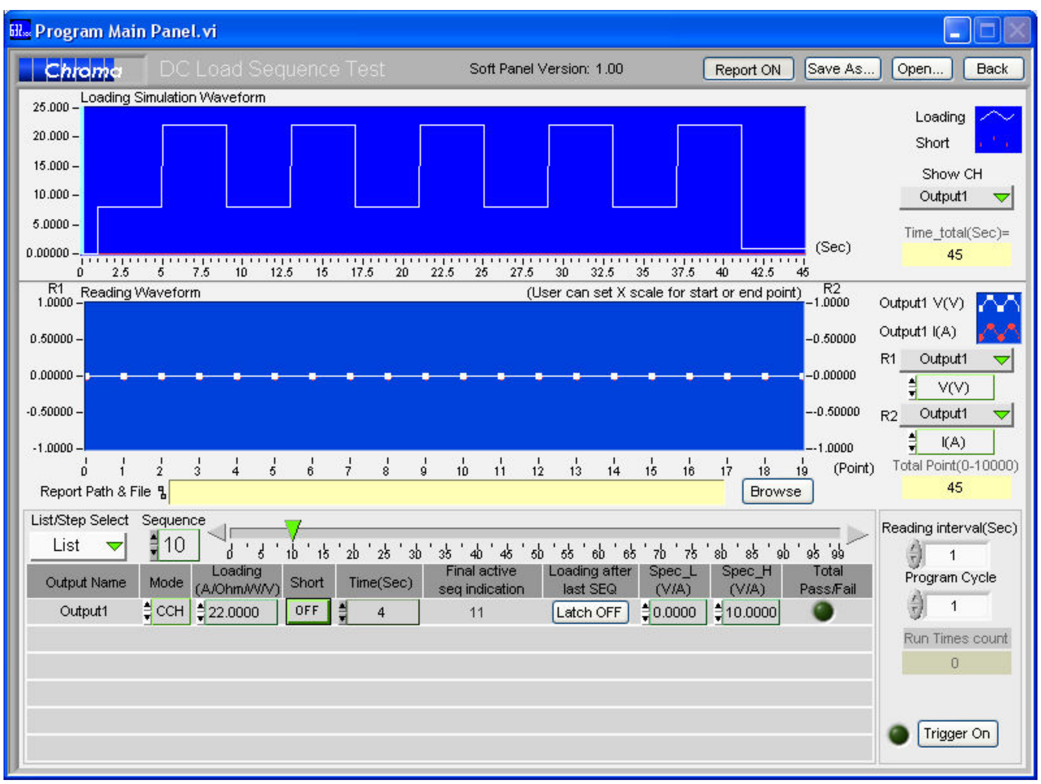

Figure 7. Panel display of user interface Chroma programmable DC load [3]

The Chroma computer software that accompanies the programmable DC load system can be used to control load current, to monitor voltage response, as well as stack current, and to log data. The above figures show the step function and square wave function that the load will be applying to the fuel cell. Additional equipment utilized includes a Bacharach Leakator® 10[1], which is a portable combustible gas leak detector, and a Tektronix TDS 2002B oscilloscope[7].

Background and theory

As described by O'Hayre et al., analysis of a fuel cell stack is carried out for two reasons: to "separate good fuel cells from bad fuel cells" and to understand why a particular fuel cell performs as it does[6]. While each of these categories encompasses a variety of possible tests, one fuel cell characterization technique that summarizes fuel cell performance is to determine the efficiency of the fuel cell stack[6]. This analysis uses the ratio of energy out over energy in.

To measure the amount of energy consumed by the system, the flow rate of hydrogen into the system is measured using the fuel cell software and the system mass flow meter. Using the following equation, the molar flow rate can be calculated from the volumetric flow rate which is given by the fuel cell monitoring software.

Eq. 6 (ideal gas law, assuming standard pressure and temperature):

$$\frac{dN}{dt} = \frac{P\left(\frac{dV}{dt}\right)}{RT}$$

where $\frac{dN}{dt}$ is the molar flow rate in mol/min, $\frac{dV}{dt}$ is volumetric flow rate in L/min, P is the pressure in atm, T is the temperature in Kelvin and R is the gas constant of 0.082 L atm/(mol K).

To compare the amount of energy out to the amount of energy in, conversion factors are used to convert the output current of the fuel cell into a molar flow rate. The following equation was used to determine a constant that could be multiplied by the current to determine the molar flow rate.

Eq. 7:

$$1A = \frac{1C}{1sec} \times \frac{1mol_{e-}}{96400C} \times \frac{1mol_{H2}}{1mol_{e-}} \times \frac{60sec}{1min} = 3.12 \times 10^{-4}\frac{mol_{H2}}{min}$$

After the molar flow rate of fuel in and fuel out have been calculated they can be used to determine the efficiency of the fuel cell as shown in the following equation.

Eq. 8:

$$\varepsilon = \frac{Useful\ Energy}{Total\ Energy}$$

Where ε is the efficiency of the fuel cell stack.

Methods

The experimental setup used to analyze the efficiency and the load response of the fuel cell is shown in Figure 8 below. The setup includes the Ulmer Brennstoffsellen-Manufacturing HP 600 fuel cell system, Chroma 63203 programmable DC electronic load, Tektronix TDS 2002B oscilloscope, and a Dell desktop computer with the HP 600 software installed. Figure 8 shows that the DC load draws current from the fuel cell stack while hydrogen and oxygen are supplied continuously. When the fuel cell operates, current and voltage signal are recorded into the oscilloscope by connecting the signal cables into the output signal terminal in the DC load.

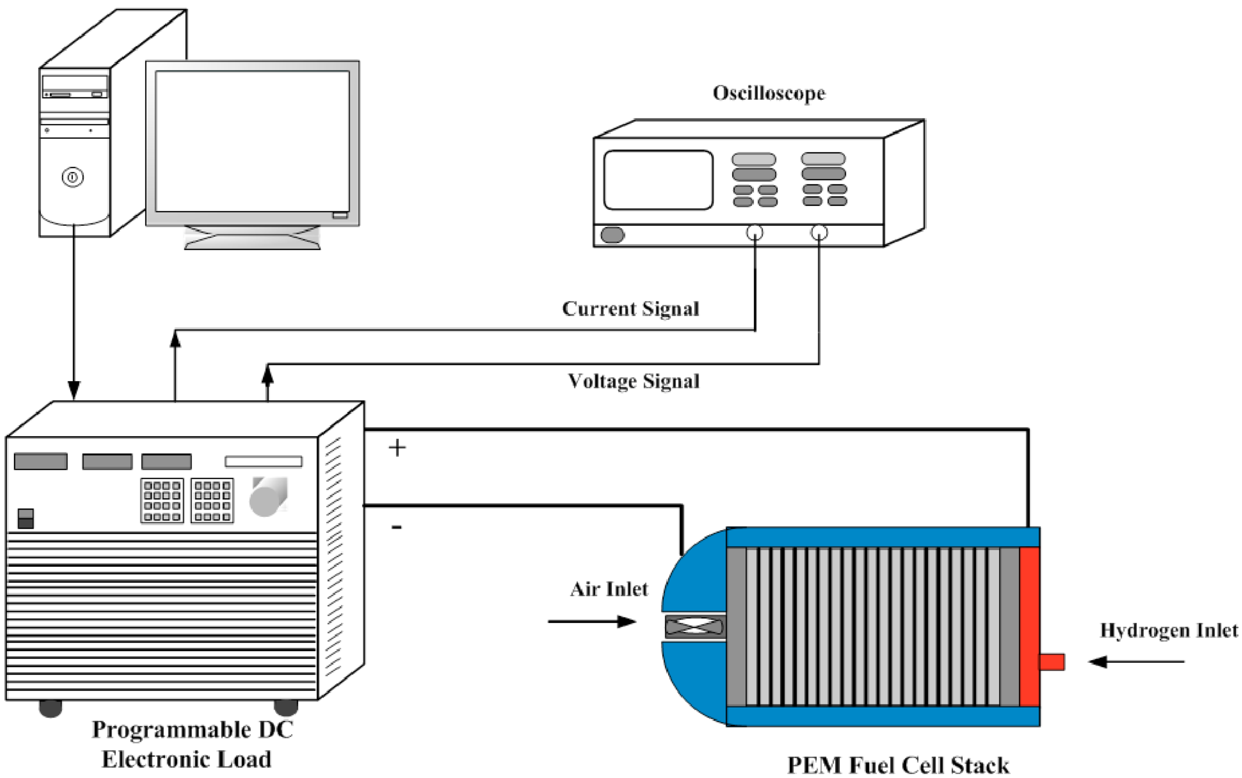

Figure 8. Experimental setup

To calculate the efficiency of the fuel cell, the system is started and allowed to warm up for 5 minutes. The electronic DC load is programmed with a step function that will increase the current from 0 to 40 amps at a rate of 1 amp per 2 seconds. The Dell desktop computer with the HP 600 software is used to communicate with the HP 600 fuel cell system via USB port. The data logging capability of the software is used to collect the data points needed. For this experiment the data points that are analyzed are the hydrogen flow rate and the stack current. These two values are used to determine the amount of energy that the system delivers compared to the amount of energy that is put into the system. For this lab the value of the energy in versus the value of the energy out is expressed in moles of hydrogen per minute. Using conversion factors from Fuel Cell Fundamentals[6], the flow rate and the current from the collected data can be expressed in moles of hydrogen per minute format. The last step to calculating the efficiency of the fuel cell is to divide the energy out (energy calculated from current) by the energy in (energy calculated from the hydrogen flow rate).

For the second experiment, an oscilloscope is connected to the programmable electronic load. On the back side of the load there are two connections for the oscilloscope, one for the voltage readings and one for the current readings. The oscilloscope is used to acquire the data, which is then transferred using a USB flash drive to an Excel spreadsheet for analysis. To see the transient of the voltage as the load is rapidly changing, the load is programmed with a square wave function that brings the current from 4 amps up to 12 amps and then back down to 4 amps.

Results and analysis

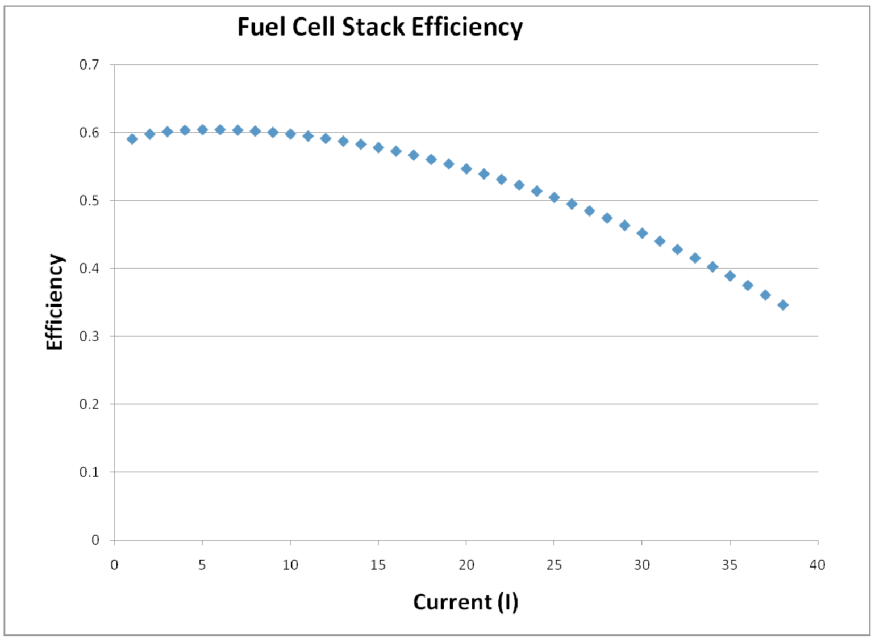

Figure 9. Efficiency results of the HP 600 fuel cell stack

The efficiency curve that was obtained for the fuel cell stack is typical for proton exchange membrane fuel cells[2]. As seen in Figure 9, fuel cell efficiency peaks around 5 to 10 amps at 60% and declines at an increasing rate as the current increases. This is an expected system behavior.

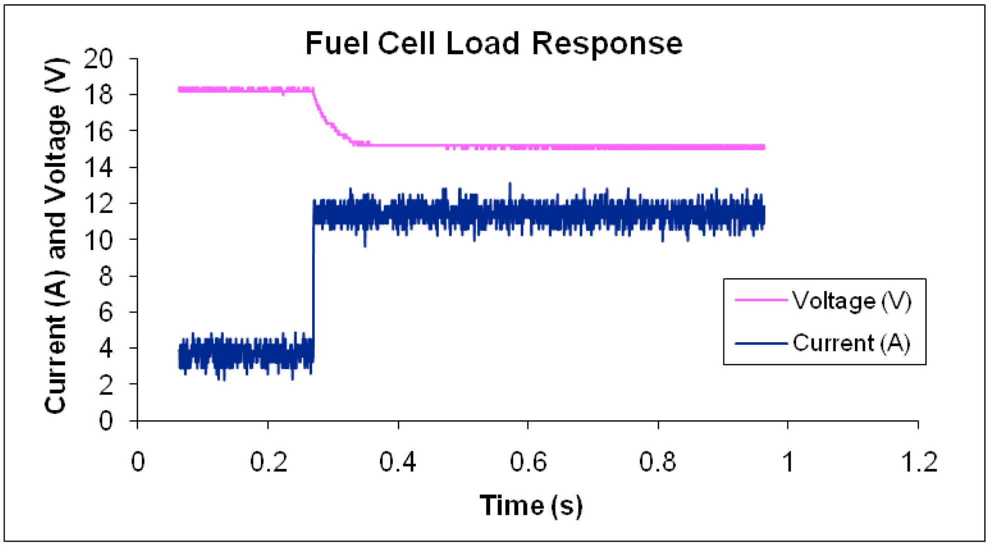

Figure 10. Transient response of the HP 600 fuel cell stack

In Figure 10, the change in current and voltage over time is presented. While the current response is so rapid as to appear instantaneous, the voltage response curve is smoother, respresenting a slower response.

Conclusions

The first experiment analyzes the efficiency of the HP 600W fuel cell. Using the current and hydrogen flow data and equations 7 and 8, the efficiency was calculated and plotted against current. Based on the efficiency curve, it is concluded that the behavior of this fuel cell is typical for PEM fuel cells. Performing this lab will give students knowledge of how the fuel cell efficiency changes with adjustments in current. Going through this lab will also give the students an opportunity to apply conversion factors using data from the laboratory.

The second experiment exhibits the ability of the HP 600W fuel cell to respond to rapid load changes. While the load increase in this experiment was relatively small for the size of the fuel cell stack, further experimentation could include greater load values to test the current and voltage responses. The importance of this lab is to show students the load following capabilities of fuel cells as load changes. Fuel cell applications such as in motor vehicles will require the capability to respond quickly to rapidly and frequently changing loads. This laboratory provided a basic understanding of the behavior of a fuel cell system under these conditions and can be used as a precursor to more involved experimentation.

When looking at both of the experiments together students should be able to see that even though the fuel cell has a maximum power output of 600W, it would not be a good solution for a 600W load. This is due to losses in efficiency and the time it take for the voltage transients to reach a steady state. This lab gives students some basic knowledge they need to design fuel cell systems for specific applications.

Recommendations and future plans

The experiments performed and presented in this paper provide an example of the type of laboratory investigation that could be incorporated into a fuel cell education curriculum. While these and many other experiments can be followed precisely, encouraging students to design their own labs or to add variations on the current design is advised.

Finally, with regard to fuel cell and hydrogen education at the University of _____, a strong recommendation is made for development and inclusion of a Hydrogen/Fuel Cell laboratory component to accompany such classes as Renewable Energy Systems and Methods of Hydrogen Production and Storage. It is the hope of the authors that this research will serve both as a motivation and as a reference for development of such a course, to be incorporated into engineering curriculum.

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