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Development of an Educational Fuel Cell System for Mechanical Engineering Course

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Abstract

Although there is growth in electrochemical system applications such as batteries and fuel cells to power land and air transportation and the current push for hydrogen technology, modeling and control design of thermal and power aspects of such systems is not commonly taught. To incorporate such content, an educational learning hardware system with software interface had been constructed to teach process dynamics and control in selected undergraduate mechanical engineering courses. Given a fuel cell is an energy conversion unit that uses chemical fuel to produce electricity without combustion, a set of student groups developed an educational laboratory system that ensured reliable and consistent power delivery from fuel cell as well as stable hydrogen production using cost-effective and off-the-shelf resources. A 100W Proton Exchange Membrane Fuel Cell (PEMFC) system was constructed through integration of hardware components, and user software interface like MATLAB for accessibility and ease of use in a laboratory course setting. The interface accessed remotely or face-to-face allowed for flow rate, pressure, and temperature measurements to be recorded for student analysis related to understanding of thermal and power performance and management of fuel cell and/or electrolyzer at different operating conditions. The system performed well based on initial testing by a pilot group of other students. It will be implemented in an upcoming course offering related to energy conversion and/or thermal fluid laboratory.

Introduction

Fuel cell technology has been playing a vital role in space exploration since the 1900s. Fuel cells serve as a reliable backup energy source whenever sunlight is not available to power the space shuttles and other space mission appliances (Tabbi et al 2016). A regenerative fuel cell (RFC) system can continuously generate power by utilizing the electrolysis process to break down water into Hydrogen and Oxygen gases (Zonghu et al 2021, Leena et al 2014). Hence, it is crucial to building an integrated balance of plants for the fuel cell to generate consistent power for a more extended period. Although this is possible at NASA facilities, such is not possible in most educational settings and facilities.

It is known laboratory-based learning allows engineering students to deduce and apply concepts such as fuel cell technology that they can learn from the classroom. However, limited access to the physical laboratory resources proves challenging for students to further explore, understand and apply such ideas and concepts at their instituitions. Moreover, hydrogen technology, modeling and control design of thermal and power aspects of such systems is not commonly taught in the mechanical engineering curriculum in the United States and around the world. Thus, introduction of experimental design project based on complex electrical power systems like a fuel cell facilitates project-based learning and exposes students to thermal fluid energy systems.

The purpose of this project was to design, model and build a fuel cell system that can serve as an energy source of a Lunar analogous rover or even an Earth based electric bike for educational purposes in selected mechanical engineering courses.

Stages of Development

The development of the fuel cell system, as illustrated in Figure 1, consists of (1) design, model, analysis, (2) testing and evaluation, and (3) applications and implementation. The fuel cell system is first designed and simulated using MATLAB and Simulink. The balance of plant along with the computer interface is to control the fuel cell system is designed and analyzed. The data acquisition system and instrumentation is then incorporated to test the fuel cell system and evaluate its performance. Finally, the system is integrated into relevant, selected courses for laboratory and project-based learning. The project could involve the implementation of a electric bike to demonstrate the fuel cell technology.

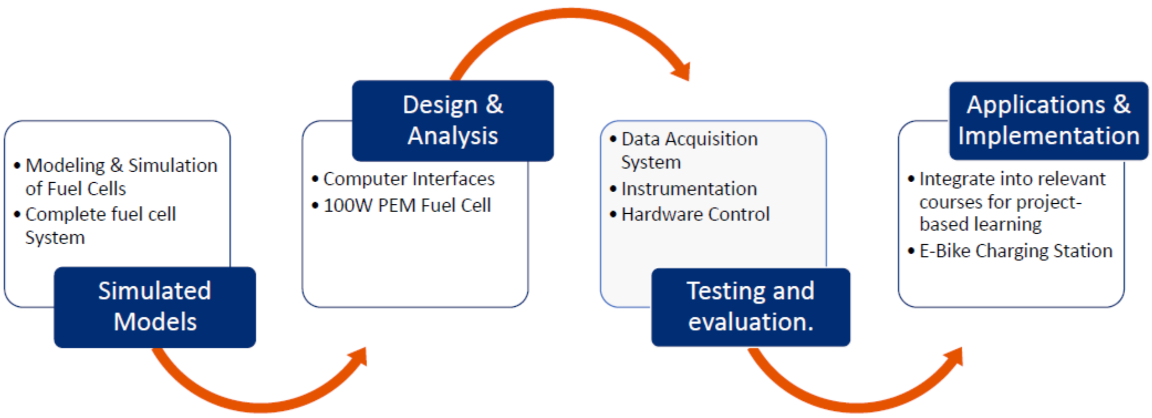

Figure 1. Stages of Development of the Fuel Cell System

Design and model analysis considerations are to account for the given specifications and nonlinear performance behavior of proton exchange membrane fuel cells (PEMFC) and electrolyzer along with physical facility conditions for testing and evaluation. Fuel cells are inherently an electrical power producing unit that converts chemical energy in the form of hydrogen fuel to electrical energy, as illustrated in Figure 2 (Marshall, 2017). Electrolyzers are reverse in operation compared to a fuel cell where they produce fuel hydrogen and oxygen from water using electrical power, as illustrated in Figure 3 (Steyn and Render, 2020).

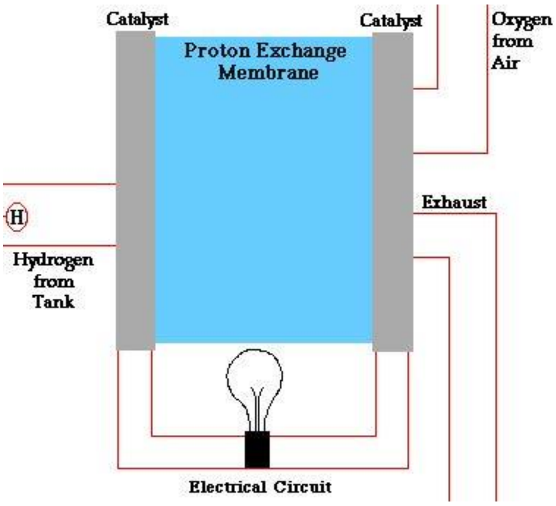

Figure 1.Schematic of PEMFC

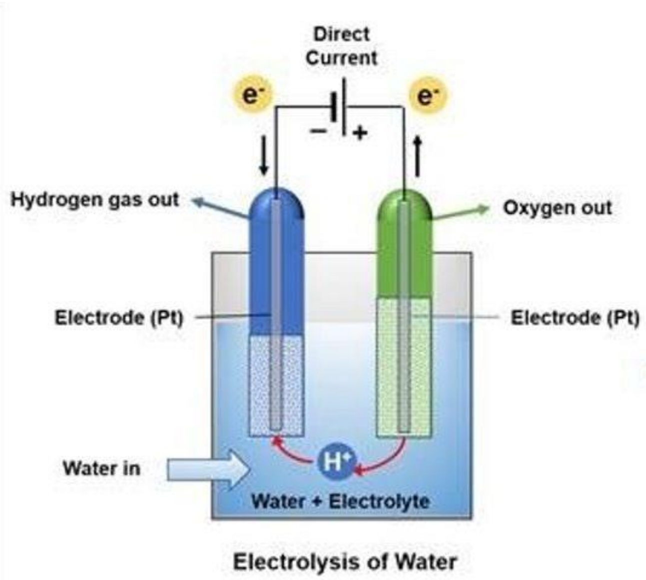

Figure 2. Schematic of PEM Electrolyzer

Design, Modeling and Analysis

For model development, the specifications of the fuel cell and electrolyzer are highlighted in Table 1 where the fuel cell produces 100 Watt of electric power operating at 12 Volt and 8.3 Amperes while the electrolyzer based hydrogen generator produces hydrogen at a maximum flow rate of 1 standard Liters per minute and a pressure of 7.2 psi. Table 2 captures the specifications and constraints for the entire system.

A simulation was conducted to produce estimated values for the 100 Watts and 12 Volts Fuel Cell Stack using MATLAB and Simulink. The PEMFC simulation values and properties were adjusted to resemble the specification of the PEMFC stack utilized in this project to give the voltage data and model plots shown in Figures 4 and 6. Figures 5 and 7 show the expected curves from the given PEMFC stack manual which is the expected performance for this project. From the Voltage-Current curve in Figure 4, the model shows the optimal performance of the fuel cell is at 8.3 Amperes and 12 Volts. From the Power-Current curve in Figure 6, it shows a peak value of 0.0996 kiloWatts or 99.6 Watts, which is very close to the manufacturer's manual value of 100 Watts (Horizon, 2013).

Table 1. Specifications for Modeling based on Given Laboratory Facility

Fuel Cell	
Brand	Horizon
Number of cells	20
Operating Temperature	65ºC
Pressure	7.2 - 8.7 psi
Max Hydrogen Flow Rate	1.4 L/min
Max Power Output	100 W
Optimal Operation	12V @8.3A
Hydrogen Generator	
Brand	Fuel Cell Store
Pressure	7.2 psi
Max Flow Rate	1 L/min
Hydrogen Purity	99.9995%

Table 2. System Constraints and Specifications for Design and Modeling

Specification	Description	Measurement Device, Units	Acceptance Criteria
Stand size.	Entire lab setup is contained in a 5ft×5ft area.	Metric	5ft×5ft area
Tubing	Must be able to handle working pressure and should not react with hydrogen	Metric, MPa	Should operate safely between 0.04−0.4MPa for 12 hrs.
Temperature	Fuel cell must remain under the maximum temperature.	Type K thermocouple, °C	Should operate below 65°C for 12 hrs.
Pressure Regulation	Pressure from the hydrogen generator to the fuel cell must be reduced.	Pressure transmitter between generator and the fuel cell, PSIG	Should operate between 7 psig−8psig.
Mass Flowrate	H2 flowrate must be measured and controlled.	Mass flowrate controller, SLPM (Standard liter per minute)	Flowrate data will be displayed. Should automatically control for the specific output.
Live Data Acquisition and Display	H2 flowrate, pressure, stack temperature, output voltage, current, and power measurement from the DC electronic load	DAQ, Sensors, Arduino Uno	Should be compatible with NI LabVIEW. Display should operate for 12 hrs.

Design, Modeling and Analysis

Following fuel cell modeling simulation, student designed and built a full fuel cell system as part of senior design course projects. The system as shown in Figure 8 included not only the 100 Watt PEMFC stack and the Hydrogen Generator (electrolyzer), but also other components to monitor, control and collect data such as the Mass Flow Controller for hydrogen flow to the fuel cell, the Electronic Load to mimic the power demand of an electric bike or a small scale rover, and an interactive user-friendly functional computer interface designed by the students in LabVIEW software. The safety codes and guidelines needed for the proper working of this project were adhered to throughout the entire design process by the students, while engineering regulations, principles, and practice were implemented throughout the building and testing stages of the project.

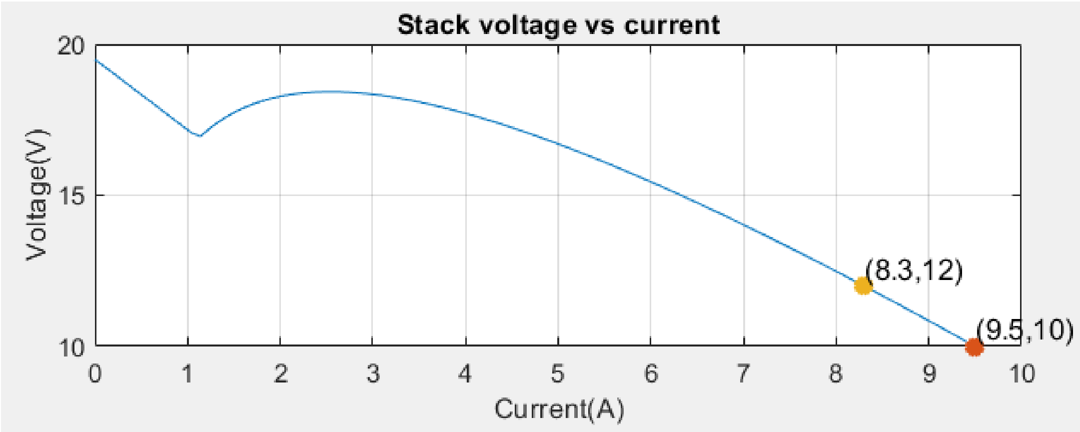

Figure 3. Plot of 100W PEMFC Voltage-Current Curve using MATLAB and Simulink

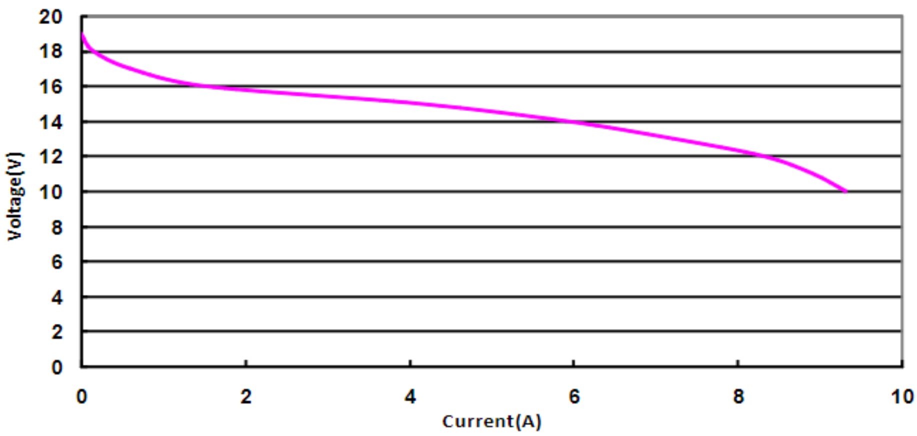

Figure 4. Plot of 100W PEMFC Voltage-Current Curve from manufacturer

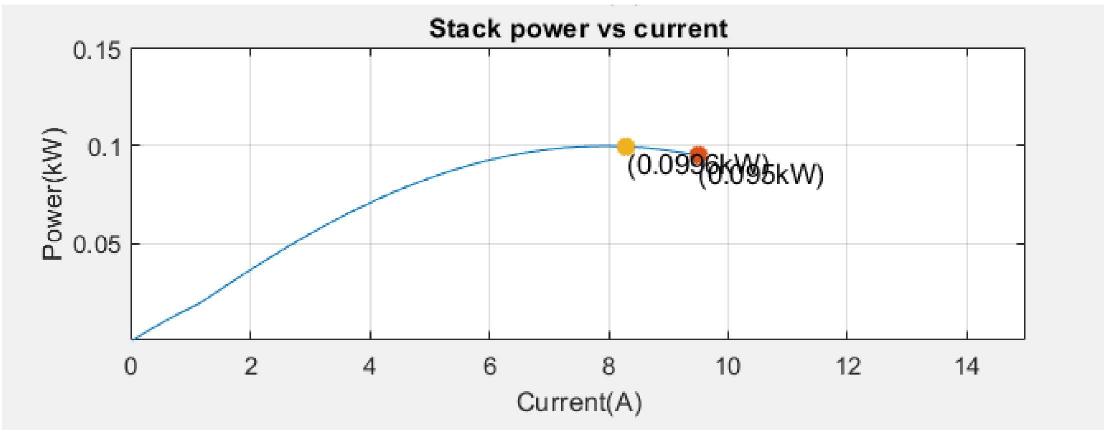

Figure 5. Plot of 100W PEMFC Power-Current Curve using MATLAB and Simulink

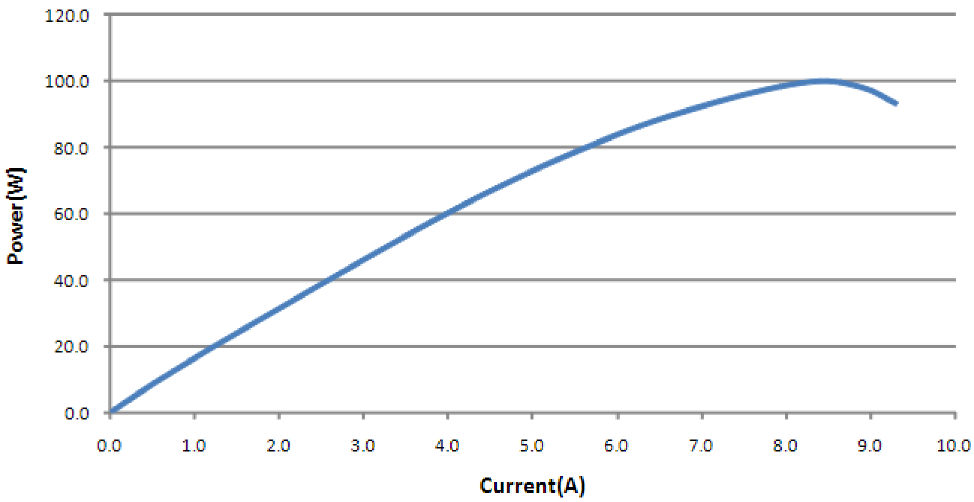

Figure 6. Plot of 100W PEMFC Power-Current Curve from manufacturer

Table 3. Safety Codes and Guidelines

Hydrogen management	ASME B31.12 code for hydrogen piping and pipelines
Boiler pressure vessels	ASME BPV code Section VIII
Pumps	API 610
Piping	CGA G4.1
Stainless steel	ASTM 316 SS

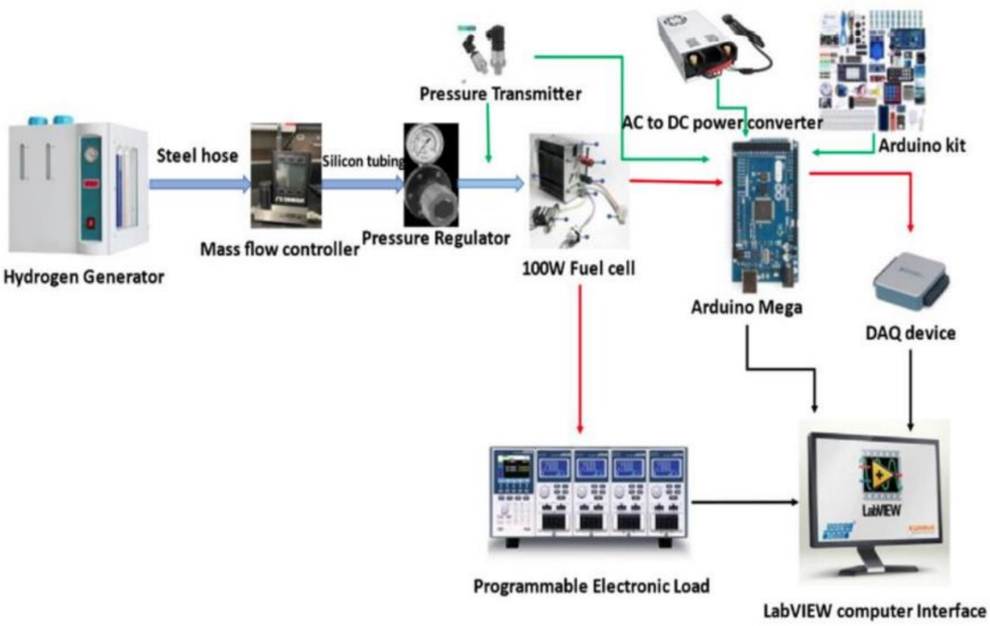

Figure 8. Designed PEMFC System Layout

All the standardized mechanical engineering associations require the use of universal units, and each of the equipment was observed as shown in Table 3. The integrated system consists of a PEMFC stack size of 20 cells with pure hydrogen and air as the primary fuel supply. The fuel cell is connected to an electric load and a hydrogen generator, in Figure 9, through a piping system that allows the hydrogen from the generator to flow through the mass flow meter, the three-way pressure transducer, and the hydrogen valve so that controlled responses from the temperature sensor and pressure transducer can be registered onto to the developed National Instrument LabVIEW interface. Block diagrams were used to represent each component of the subsystem and how the actual system will be connected in space during actual operation. The electrical connections in the electrical board in Figure 10 were handled with all the safety principles and methods observed in the laboratory safety manuals. Due to the difficulty encountered during the component testing process, a decision was made to combine an Arduino Uno, in Figure 11, to control flow rates with the LabVIEW software based on the specifications and constraints.

Figure 7. Side View of Hydrogen Generator (top) and Internal View of the Electrolyzer Compartment in Hydrogen Generator (bottom)

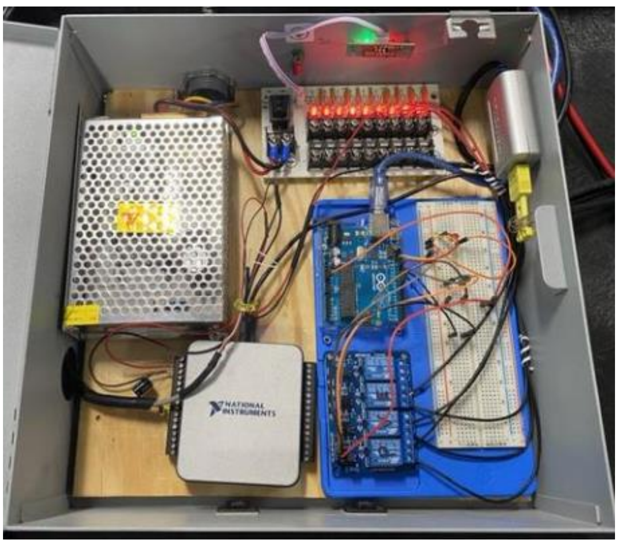

Figure 8. Electrical Board Including Data Acquisition System and Controller Setup of the System

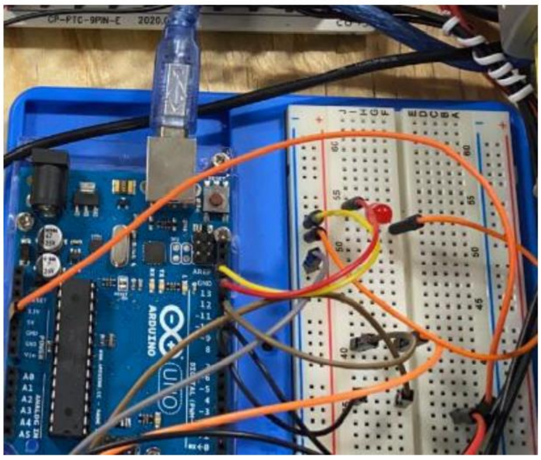

Figure 9. Arduino Uno Setup to Control the Fan and Valves in the Electrical Board for the Fuel Cell System

Figure 12 shows a block diagram in LabVIEW that enables tests to be performed by using a programmable language through its LabVIEW interface. The software has a graphical manipulative instrument that allows systems to visualize the physical system in real time testing conditions. This way, LabVIEW can integrate measured data and present it through diagrams, blocks, and codes by connecting these designs icon in such way to indicate the systems and the subsystems in a logical pictorial format in its interface. This platform is used to design, build, and test system without necessary being with the physical system. Figures 12 ,13 and 14 show the actual developed block diagram for integrated system in LabVIEW. The LabVIEW software is used to create icons in the form of block diagrams so that the component in the system is represented. Each subsystem is assigned to a block diagram in the LabVIEW interface to represent the physical components so that signals are relayed, and data are recorded on the LabVIEW user interface as shown in Figure 15. This system prototype was tested using the layout presented in Figure 8.

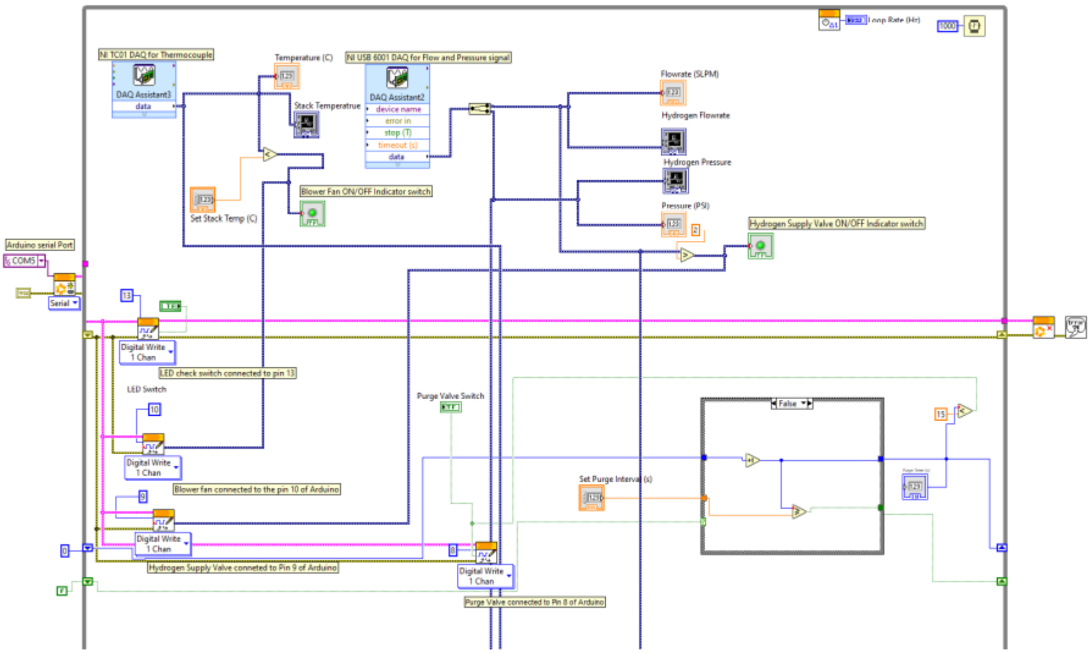

Figure 10. Block Diagram Showing the Integrated System (part 1)

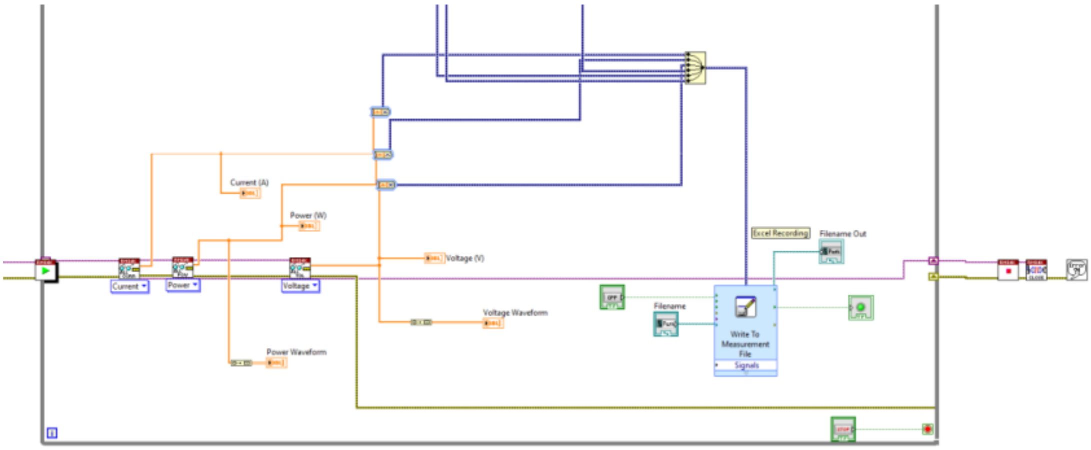

Figure 11. Block Diagram Showing the Integrated System (part 2)

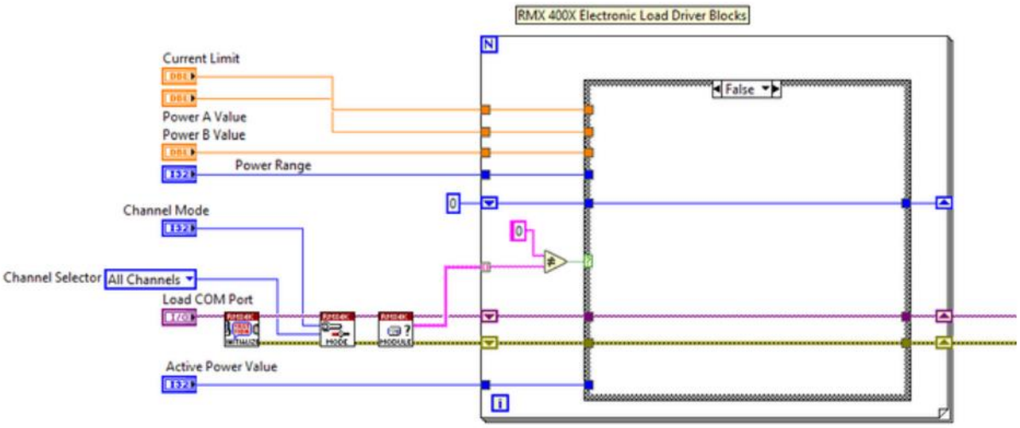

Figure 12. Block Diagram Showing the Integrated System (part 3)

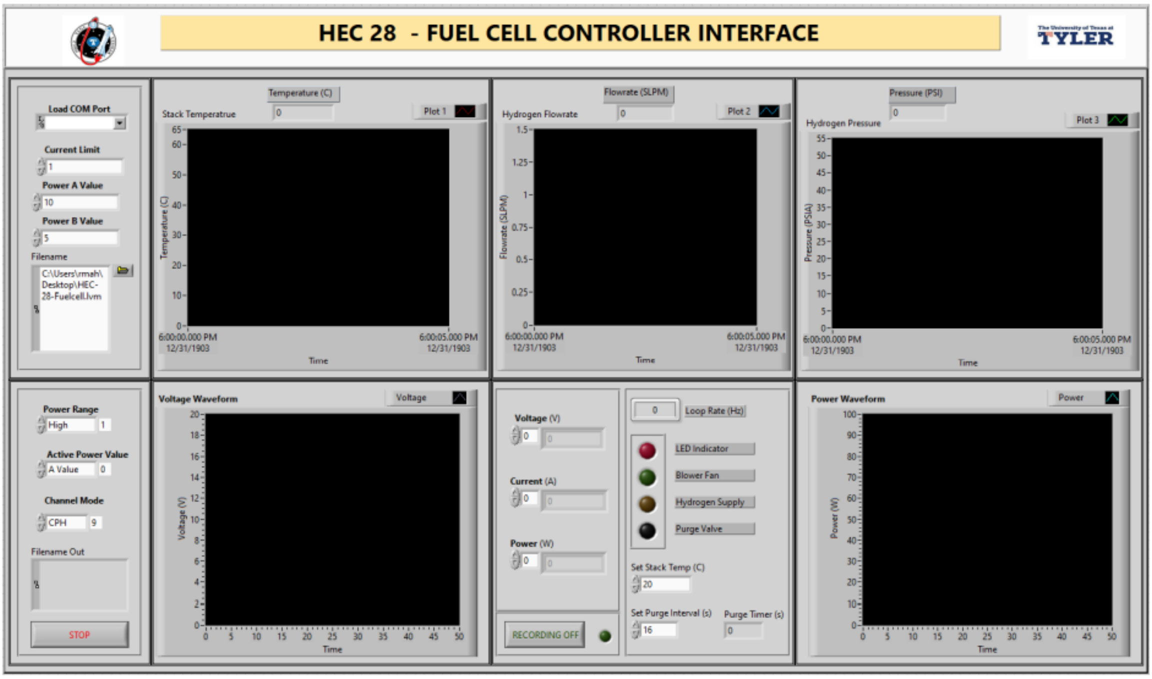

Figure 13. Measuring Indicators on the LabVIEW User Interface for Fuel Cell System

Prototype Testing Results and Discussion

The system instruments and sensors from the fuel cell and hydrogen generator are connected to a data acquisition device (DAQ), where incoming signals from sensors are fed through it and displayed as output data on the constructed LabVIEW user interface as shown in Figure 16. It shows data such as the temperature, pressure, flow rate, voltage, current, and power. In addition, it could manage the hydrogen supply valve, purge valve, LED indicator, and blower fan. Figure 15 shows the interface turned off and Figure 16 demonstrates the interface when turn on and displaying the various graphs in a certain time frame. The in-lab testing setup was a continuous evolving operation due to factors that emerged, such as items needing reconfiguration and parts needing extra components to function properly the setup is important to the overall project for its visualization and how the system should work while keeping everything organized as best as possible. The complexity of the in-lab setup becomes increasingly intricate as the system becomes functional due to sensitive add-ons. The arrangement of the pieces was important, such as locating errors that might pop up in the system.

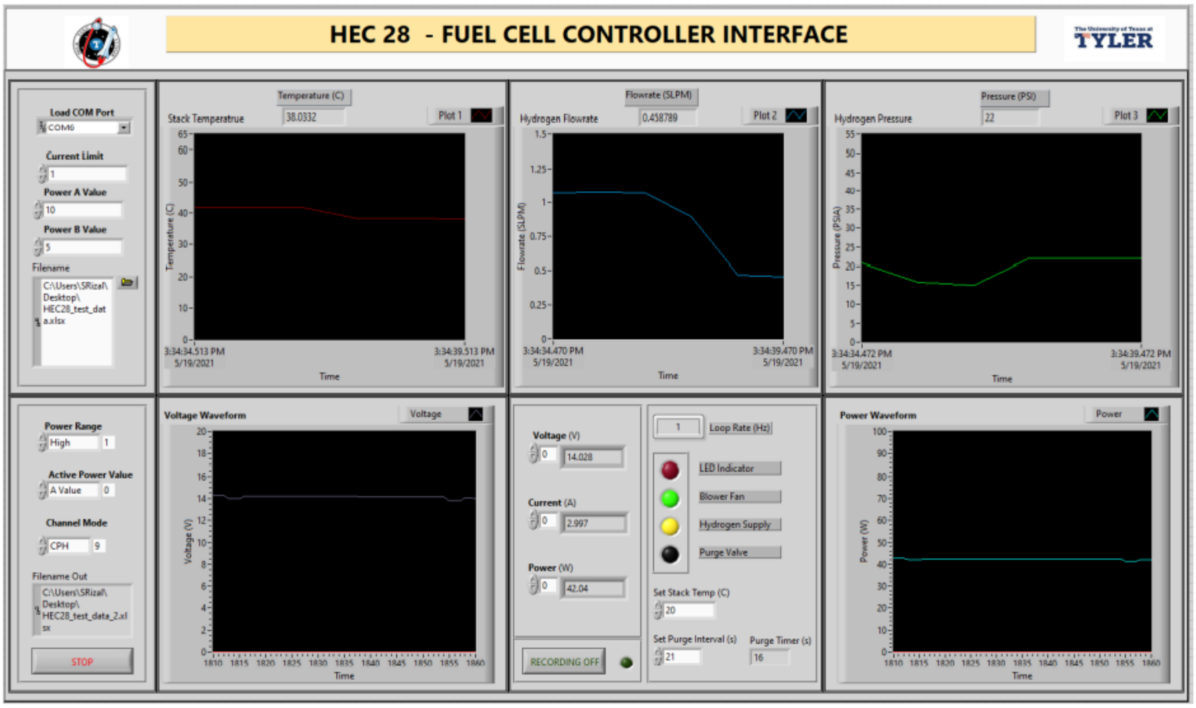

Figure 14. LabVIEW User Interface During Testing of Fuel Cell System

For the Power-Current curve collected from the experiment, Figure 17 shows that increasing the current (A) will also increase the power output (W) of the fuel cell. However, you can see in the graph that the curve peaks and drops off. This means that the fuel cell's optimal performance for a 100 W power output is rated for a current of 7.2 A. In the in-lab testing graph, this phenomenon also occurs but not in the fashion depicted in the horizon manual none the less it demonstrates the increase of power when current rises.

There were several hardware to software complexities that had to be addressed as mentioned earlier including use of Arduino Uno instead of National Instruments DAQ for fan and valve control. Moreover, the ease of use of the user interface to monitor and control the fuel cell system can be improved by adding more features. Finally, there needs to be facilitating of real-world examples beyond an electronic load to mimic a small vehicle to demonstrate the use and application of fuel cells more effectively.

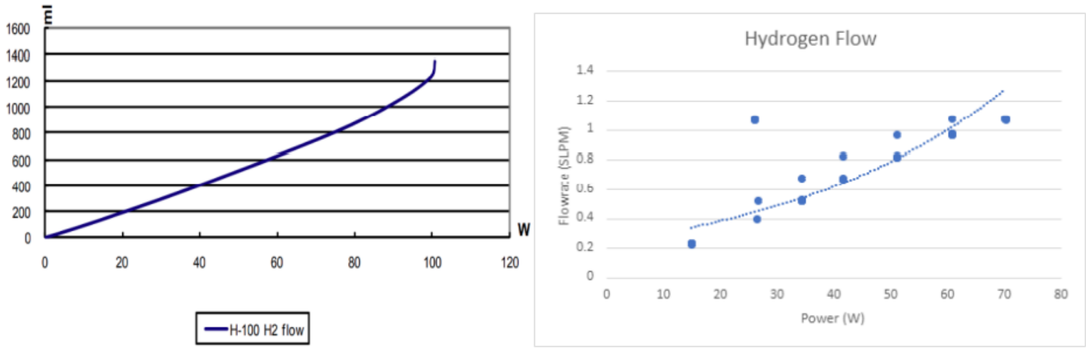

Figure 15. Hydrogen Gas Flow Curve from Horizon Manual (Left) and In-lab Testing (Right)

Conclusion and Implementation Plan

To streamline hardware control and data acquisition a new laboratory system is to be developed called the "Universal Laboratory Interface Device." This system will allow for high modularity along with plug and play option for the existing physical fuel cell system along with other systems such as heat exchanger and fluid mechanics laboratory units. There will be further incorporation of the completed system into curriculum of selected mechanical engineering courses include Thermal Fluid Laboratory to learn about thermal fluid management of a fuel cell system and Energy Conversion to learn to model and analyze an electrochemical system such as a fuel cell and an electrolyzer. Finally, the plan is to design E-bike charging station to explore and test in selected mechanical engineering courses.

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