Instrumentation of a PEM Fuel Cell Vehicle

Bruce Sun, Wallace Turner, Micheal Parten   Tim Maxwell
Electrical and Computer Engineering   Mechanical Engineering
Texas Tech University

I. Introduction

Electric vehicles have long held the promise of zero emission vehicles. However, battery powered electric vehicles have not been accepted by the general public, in large part, because of their very limited range. A hydrogen-based, fuel cell could provide the power necessary to give an electric vehicle the same range as a modern gasoline powered vehicle. In this case, a fuel cell is a device that converts hydrogen into electricity by a simple oxidation reaction. The products of the electrochemical process are electricity, heat and water. In a fuel cell powered vehicle, an equivalent series hybrid power train provides the driving power to the wheels. Both the battery pack and the PEM fuel cell system supply power to the motor and motor controller. Since the output electrical power of the fuel cell stack is designed to exceed the average power demands of the vehicle, the batteries can be charged while driving. The range of the vehicle is then tied to the amount of hydrogen or fuel that is on board. A fuel cell powered vehicle consists of the integration of many complex nonlinear systems. The power train, generally, contains a proton exchange membrane (PEM) fuel cell stack with its accessories, a DC/DC converter, battery pack, motors and motor controllers. A PEM fuel cell stack is, itself, a complex electrochemical system.[1-4]

Over the past several years, Texas Tech University's Advanced Vehicle Engineering Laboratory (AVEL) has converted five conventional vehicles to HEVs and alternative fueled vehicles for the various Vehicle Challenges sponsored by the U.S. Department of Energy (DOE), the three major U.S. automobile manufacturers, the Society of Automotive Engineers and Natural Resources Canada.[5-9]

Of particular interest today is the popularity of full sized sport utility vehicles (SUV). These vehicles are reversing the trends, over the last few years, of reduced emissions and improved fuel economy. In line with these problems, recent work at AVEL has included the conversion of a 2000 model General Motors Suburban to a fuel cell powered vehicle.

The development of the vehicle is a multidisciplinary project with students from mechanical engineering, electrical engineering and computer science involved. The majority of the team members are enrolled in a two-semester senior design sequence. However, some graduate students and volunteers also participated in the program. Faculty advisors from both electrical and mechanical engineering provide guidance for the team.

The fuel cell's performance is directly related to a large number of factors, which must be monitored and controlled. In this application, a modular LabVIEW Virtual Instrument is used to

monitor and control these parameters. The conditions that are being monitored include stack temperature; hydrogen pressure, humidity and temperature, air pressure, humidity and temperature; water ionization, and fuel cell integrity. Many of these factors must be tightly controlled to assure proper operation of the fuel cell.

II. Powertrain

In this application, the fuel converter is a PEM fuel cell manufactured by Honeywell. The fuel cell system is a combination of six sub stacks providing a total peak electrical output of 80 Kw. Each of the six stacks contains 105 cells. The electrical arrangement of the six fuel cell stacks can vary. For this application the arrangement is 2 parallel groups of 3 sub stacks in series. The corresponding output voltage under load is approximately 220 V. These systems are then wired, via a DC-to-DC converter, in parallel with the battery box to charge the batteries.

The battery system consists of 20, 12 volt, 55-amp hour gel cell batteries. These batteries are arranged in series to produce a total box voltage of 240 volts, which is the operating voltage of the three drive motors. These batteries were chosen because of their capacity, relatively lightweight, availability and cost. The vehicle receives all of its drive power from two electric motors. A 78kW motor drives the rear differential and a 70 kW motor powers the front differential. Each motor has a separate controller. A block diagram of the electrical system is shown in Figure 1.
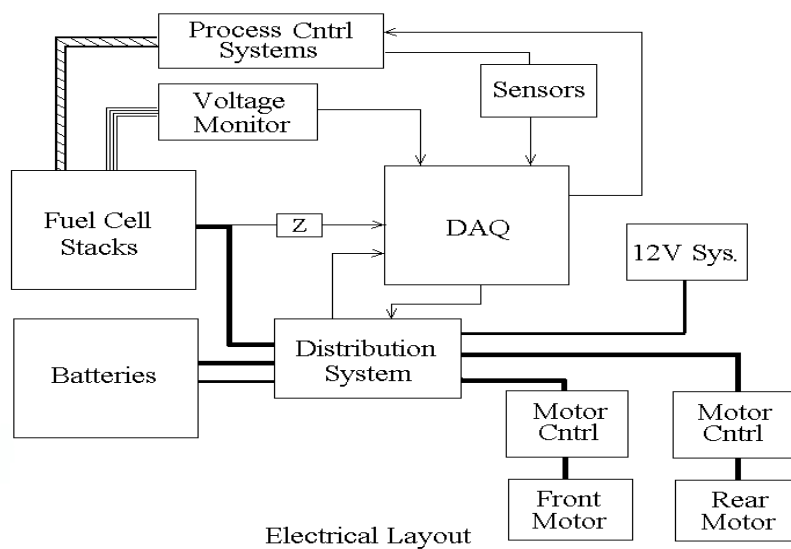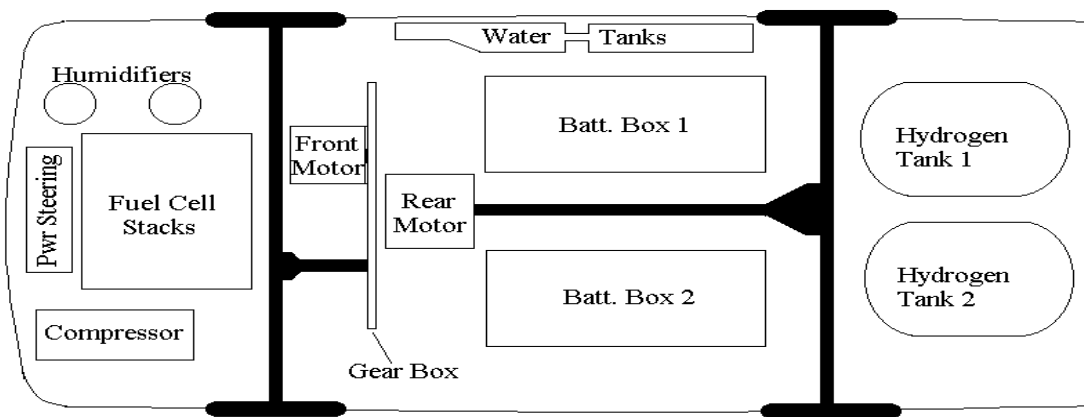

Figure 1. Electrical System

The placement of a few major components determined the location of other parts of the vehicle. Two, eighteen-inch diameter hydrogen tanks are used to carry the fuel. They are located between the rear frame rails, behind the rear axle, and protrude four inches in the rear cargo area of the Suburban. A three-inch body lift was installed to accommodate the large diameter hydrogen tanks.

However, the increased room also allowed additional room for extra batteries, and larger motors. The batteries were the next major component and are located between the frame rails, behind the torsion bar cross member, and in front of the rear axle. The fuel cell assembly is mounted in the former position of the engine, and consumes approximately 7.5 cubic feet of space, while the original engine only consumed 6 cubic feet. The cooling side of the fuel cell contains several high volume items, such as the de-ionized water pump, and the heat exchanger. The factory radiator is utilized and a second heat exchanger is mounted next to the radiator in order to operate a dual loop cooling system. Several other key elements are the humidification chambers, which are located next to the firewall, in the engine compartment. Figure 2 shows the relative placement of the components.

Under Carriage Layout

Figure 2. Component Placement

III. Fuel Cell System

The hydrogen PEM fuel cell uses hydrogen gas (fuel) and oxygen gas (oxidant) and produces electricity, water, and heat. A block diagram of a fuel-cell stack system is shown in Figure 3.

The amount of hydrogen diffusing across the membrane is directly related to the current from the cell. In the PEM fuel cell, the gases enter at the electrodes, which are porous. Hydrogen enters at the anode electrode, and oxygen at the cathode electrode. At the anode, the positive hydrogen ions diffuse across the membrane of the fuel cell while the electrons flow to the load. Hydrogen diffuses very quickly, increasing its reaction probability. The voltage output is optimized when the reaction uses as much of the surface area of the electrode as possible. The positive hydrogen ions, once they have diffused across the membrane, react with the oxygen at the cathode, producing water and heat. A small amount of water is also produced at the hydrogen electrode. Water is carried out of the fuel cell as vapor, provided none has condensed within the cell. The fuel cell membranes must remain moist, but cannot be flooded.
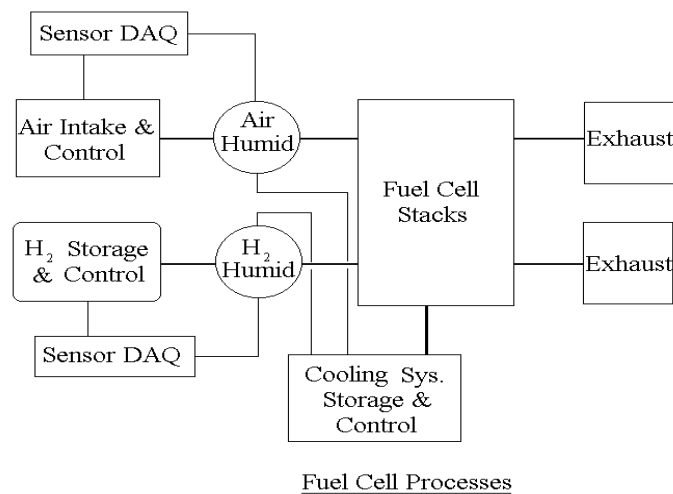
Fuel Cell Processes

Figure 3. Fuel Cell System

A PEM fuel cell can generate between 0.6V and 0.8V under typical operating conditions. The fuel cells are connected in series to form a stack to which a hydrogen-rich fuel gas and oxidant are fed by means of a manifold system.

The fuel cell's many requirements give rise to numerous auxiliary systems. The fuel cell requires the flow of hydrogen and oxygen or air. However, these gases must be within a fixed pressure range and very close to the same pressure to prevent damage to the cell. The hydrogen is carried on board in highly compressed state so that it only needs to be regulated down to the necessary pressure. The air, on the other hand, must be compressed. In addition, the flow rate must be controllable since the flow is directly related to the current produced. This requires a special high-speed compressor. In addition to these requirements, both gases must be humidified to high level to assure the membranes do not dry out. This requires humidifying chambers with injected de-ionized water. The water pressure for the injection must exceed the gas pressure, which requires additional pumps.

Hydrogen Supply System

The storage devices for the hydrogen supply are two 3600-psi tanks, specially manufactured for this application by Quantum/IMPCO. The tanks are designed to expand when filled, so specially designed brackets were made to compensate for this expansion. Each tank contains an internal regulator that contains pressure and temperature sensors, along with two sets of valves. One set, the high-pressure valve, is only opened when filling the tank. The low-pressure valve is opened when the cell is in operation, or for leak testing purposes. The hydrogen pressure is controlled by a dome-loaded regulator. From there the hydrogen travels through a humidifier, and into the fuel cell. Upon exiting the cell, excess hydrogen travels through a flame arrestor and exits to the rear of the truck. If any type of hydrogen leak is detected, solenoid valves near the tanks are closed to prevent further hydrogen flow. Figure 4 shows a block diagram of the hydrogen delivery system.
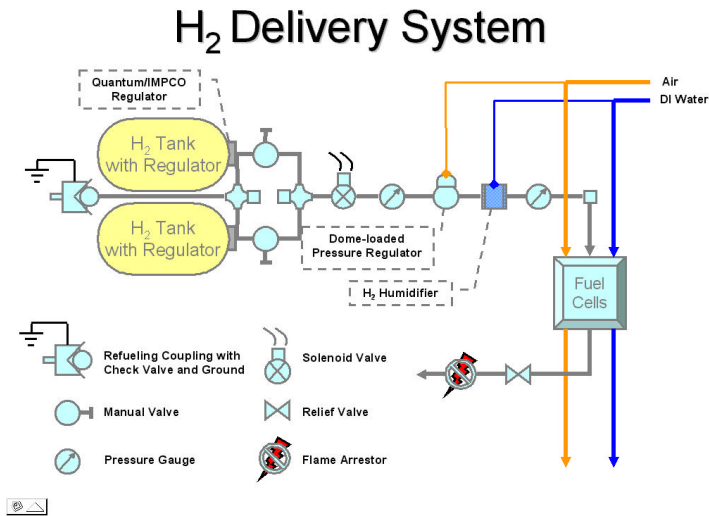
H₂ Delivery System

Figure 4. Hydrogen Delivery System

Sensors are used to monitor the temperature and pressure on each hydrogen tank. In addition, the humidity and pressure are monitored on the hydrogen input to the fuel cell. All of these signals are monitored by the LabVIEW program. The program also controls the solenoid to turn the hydrogen flow on and off. Hydrogen leak sensors are used as separate devices, which currently are not connected to the monitoring system.

Air Compressor

The air compressor can be called the backbone of the hydrogen fuel cell system. To keep from rupturing the membranes of the cells, the pressure of hydrogen on one side of the cell has to be precisely matched with the pressure of oxygen on the other side of the cell. This is done using a dome-loaded regulator that matches the pressure of the hydrogen to the pressure of the oxygen created by the air compressor. Thus, when there is no air pressure, there is no hydrogen sent to the cell, and therefore no electricity produced. Consequently, the pressure that the air compressor creates is analogous to the pressure a person puts on the accelerator of a normal vehicle.

The air compressor that is used in this system is unique in many aspects. It was manufactured by Opcon as a prototype, and was never put into mass production. Consequently, there is limited information available for the compressor. A Fischer 3-phase AC induction motor and a Samico motor controller, powered by 240 Volts, drive the compressor. Figure 5 shows a diagram of the air system.

Figure 5: Air System

The pressure and humidity of the air entering the fuel cell are monitored by the LabVIEW program along with the temperature of the air from the compressor.

Fluid System

As was stated previously, operation of the fuel cell requires a fluid system to cool the cell, and provide humidification for the hydrogen and oxygen. The fluid system in the truck consists of a DI water system to cool the cell and provide humidification, a standard radiator, and an added heat exchanger containing glycol to cool the water.

Figure 6. Fluid System

Removal of heat depends on the physical heat conduction of the fuel cell material. Alternately, a coolant is necessary for heat removal. In this case, the cooling fluid in the fuel cell runs through the electrodes, so it must have a high resistivity. De-ionized water is the most obvious choice, since it is also required for humidification. The pipes must not contaminate the water and the water must be continually filter to assure it maintains a high resistance. Also, the water is used up in the humidification process and must be periodically refilled.

The main pump for the system is powered by a 12V, 40A DC motor, which currently has been tested to produce 16-psi of pressure at 36-gpm in the closed system shown in Figure 6. This pump sends DI water to a filter, through the hydrogen cell, through a heat exchanger, and back to the water tanks. LabVIEW controls the pump and the pressure of the DI water.

Water, at a lower temperature, circulates through the cell to cool it. The flow rate of the water is directly related to the rate at which water can take the heat away. Keeping the temperature of the cell in its operating range optimizes the efficiency of the fuel cell. However, the water pressure must remain relatively fixed, which means the flow rate is basically constant. In order to meet these needs and still vary the heat removal, a double cooling loop is used. The water heats glycol through a heat exchanger, and the glycol is cooled through the radiator. The flow of the glycol can then be used to adjust the heat transfer.

In addition to the DI pump, four booster pumps are used when higher pressures or flow rates are necessary. Three of the pumps are for the DI water system: one for pumping water to the air humidification chamber, one for pumping water to the hydrogen humidification chamber, and one to pump water to cool the air compressor. The fourth booster pump is used to pump glycol through the radiator and heat exchanger to cool the DI water. All of the pumps are controlled by LabVIEW, and are isolated by solid-state relays.

Water level sensors are used for the de-ionized water tanks and the humidifiers. Temperature sensors are used to measure the temperature of the de-ionized water entering and leaving the fuel cell. Pressure sensors are used to measure the de-ionized water pump. A conductivity sensor is used to measure the conductance of the de-ionized water.

Voltage Monitoring System

In order to monitor the performance and safety of the fuel cell, the cells are monitored in groups of three to produce 210 measurements. The 210 measurements must be made every 1.5 seconds. The hardware for the voltage monitoring system consists of 24 high-voltage boards, one multiplex board and a Motorola MC68HC912B32 (HC12) microcontroller. The block diagram for the system is shown in Figure 7.
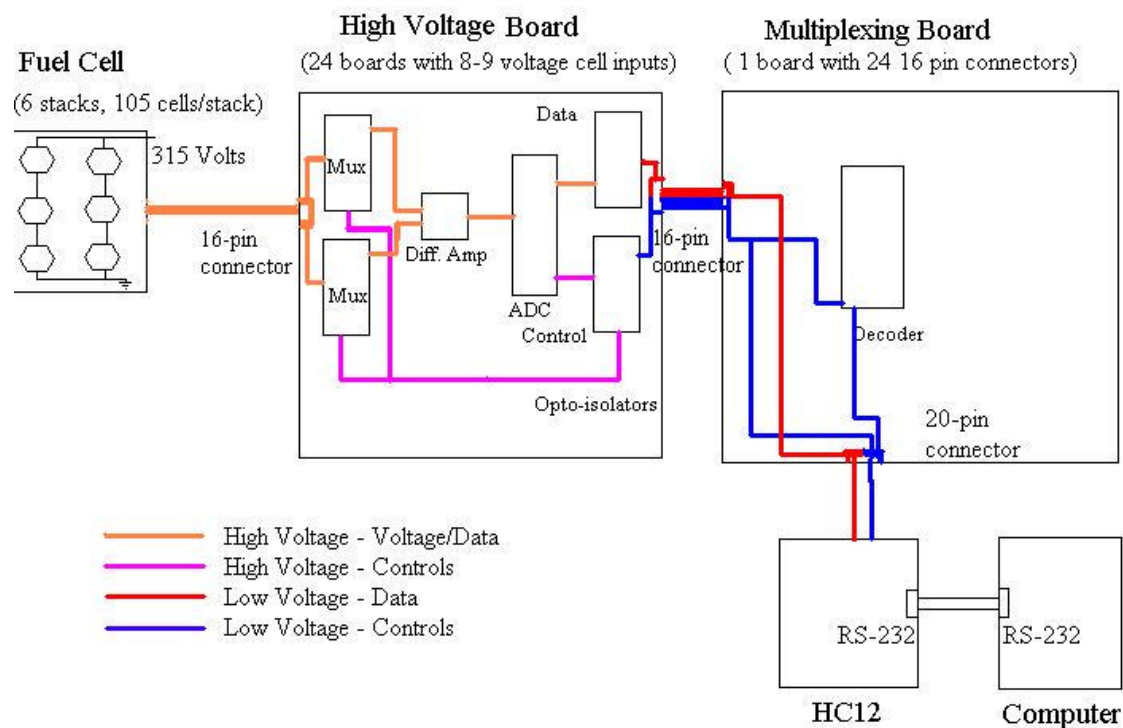
Figure 7. Voltage Monitoring System Diagram

The idea for the voltage monitoring system is to take the potential for a group of three cells and find the difference between it and the group of the three previous cells. This data is then sent to a computer. There are 24 boards that take the voltage measurements from the fuel cell and one board that is used to control the high voltage boards, receive the data and send the data to a computer through the use of the HC12. There are 4 high voltage boards with 3 boards taking 9 voltage readings and the fourth taking 8 readings. The voltages potentials are passed through an analog multiplexer. The control signals for the multiplexers come from the HC12. Each group of cells is connected to both of the multiplexers, but is offset by one gate. This allows the same control signal to be used for both of the multiplexers, with a differential pair as the output. Another aspect that must be considered is that the inputs to the multiplexers must be between positive and negative 20 volts. To achieve this, the middle group of cells is connected to the reference ground for each board.

The outputs of the multiplexers are tied to a differential amplifier. The voltage difference is then converted to a digital signal through a tri-state A/D converter. This allows the outputs of each of the 24 converters to be tied together without additional multiplexers to select the different data inputs for the HC12. The data and control lines are isolated between the high voltage boards and the multiplexer board with the use of opto-couplers. Isolation is used to protect the HC12 from any potential voltage spikes from the high voltage side and to isolate the 12-volt system of the vehicle from the high-voltage system. The multiplexing board contains two 4-to-16 line decoders to select between the 24 different A/D converters. Each decoder controls twelve of the converters. Having the HC12 enable one decoder at a time and then selecting the specific converter with the four control lines performed the decoding.

The HC12 is used to speed up the connection from the hardware to a data interpretation software program that displays the data to the user. A program, such as LabVIEW, is too slow to directly control the system and read the data. The HC12 is mainly used as a multiplexer to select the different groups of cells and to choose the A/D converter to read. The HC12 selects multiplexer control lines to select between 9 different groups of cells on each board and increments decoder lines to select between 24 different boards. The HC12 then sends the data to a computer through and RS-232 cable.

The program sends a byte of information through the serial port to the LabVIEW program. The LabVIEW program is the actual data interpretation program that compares the input values to values set by Honeywell to tell if the fuel cell is operating correctly. The nominal value for a cell under no load is l-Volt. Since the system reads in three cells at a time the nominal voltage should be 3-Volts. The LabVIEW program indicates a warning if the voltage becomes greater than 3.3 Volts and indicates a critically high voltage if the value goes above 3.59. On the other hand, the voltage can drop to .6 Volts under heavy load. The LabVIEW program indicates a low voltage warning at 1.6 Volts and a critically low voltage at 1.4 Volts. The program also determines the average voltage and the total voltages for stacks 1-3 and 4-6.

The LabVIEW code provides a graphical way of displaying the voltages and makes it easy to determine how the fuel cell is behaving. The display allows quick identification of any under performing groups of cells. It is necessary to easily identify these bad cells in order to prevent damage to the complete fuel cell. The LabVIEW code also makes it easy to determine the overall performance and capabilities of the fuel cell when it is under load. The display is shown in Figure 8.
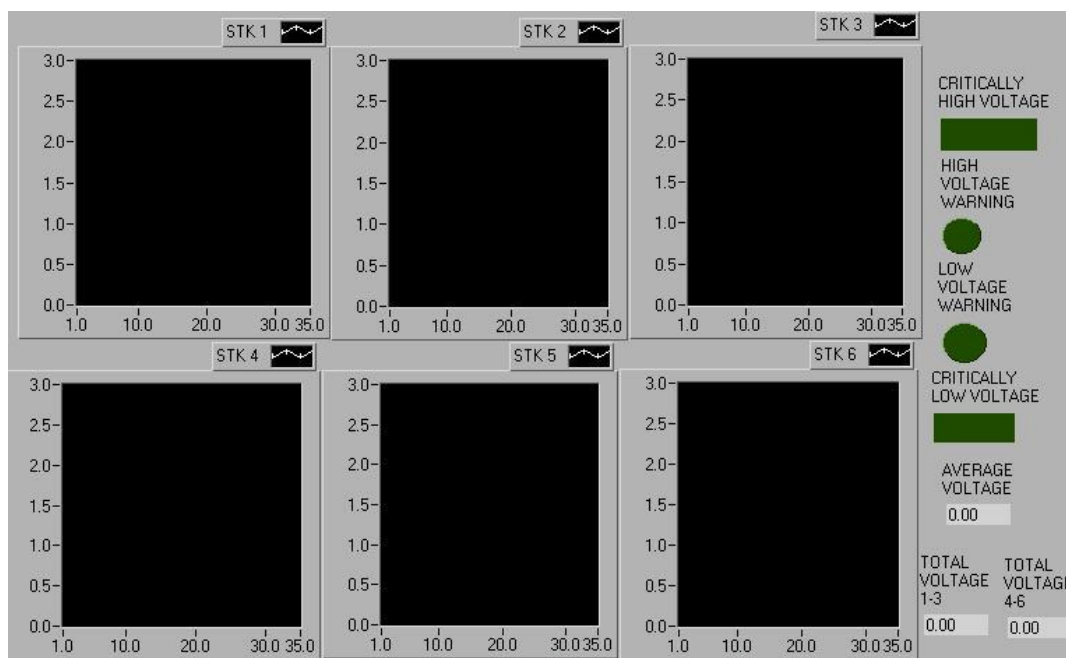

Figure 8. LabVIEW Display Panel

Control System

National Instruments' 7030 real–time data acquisition system with a 6030E daughter board was chosen for the system controller. A back plane system from Bonavio was also selected. Back planes have a smaller footprint and are more customizable than typical PCs. The Single Board Computer (SBC) placed on the back plane contains an Intel Pentium 233 MMX processor and 64MB of RAM. The system selected also has the option of adding 72 MB of flash disk. The NI controller runs in the new LabVIEW RT programming environment. The controller is programmed in LabVIEW, which allows a direct transition from simulation to the actual control program. The system also includes an expansion board, which quadruples the number of analog output lines.

A laptop computer can be plugged into ports built into the passenger compartment to log the data from the system controller. The system controller computer interfaces with the laptop via a serial port. Ports for a monitor, keyboard, and mouse are also included to provide an interface directly with the controller computer.

A screen view of the overall monitoring and control program is shown in Figure 9.
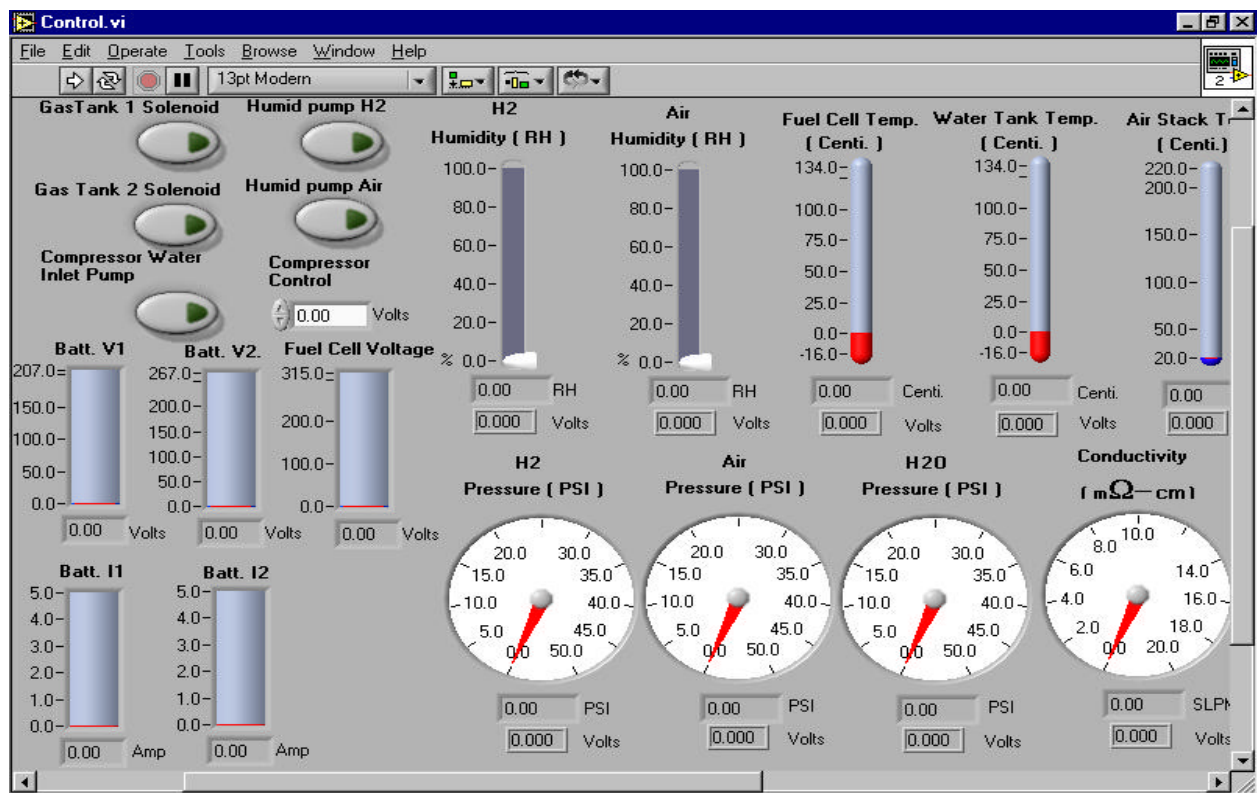
Figure 9. Fuel Cell Monitoring

IV. Results

Testing the fuel cell consisted of three phases; the first phase consisted of producing electricity from the fuel cell, but not under load. The second phase consisted of using the fuel cell to power one of the electric motors and spin the wheels, but not to place the vehicle under load. In the third stage the vehicle was placed on a dynamometer and the fuel cell was operated under load from the dynamometer while driving the motor. During the first two stages of testing the fuel cell was able to produce a maximum of 300 Volts and no problems were detected with any on the individual groups of cells. In the third stage of testing, when the fuel cell was placed under load, the voltage-monitoring system found problems with the last 3 groups of cells on both of the bottom stacks. The voltages on these cells dropped to almost 0 Volts when the vehicle was put under heavy load. The voltages on these cells also remained around 1 Volt while the fuel cell was being powered down and the rest of the cells dropped to low voltage.
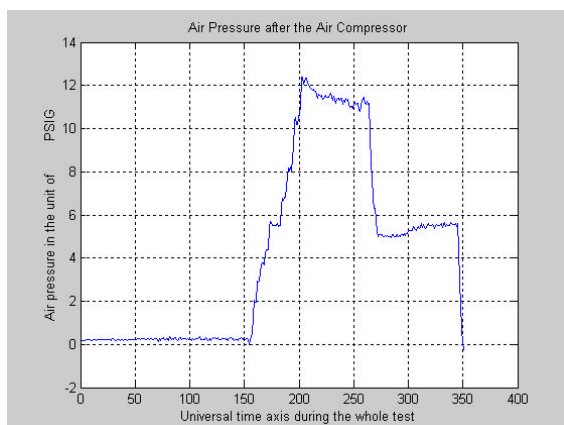
The graphs shown below are sensor results during testing of the fuel cell in the vehicle under a light load.
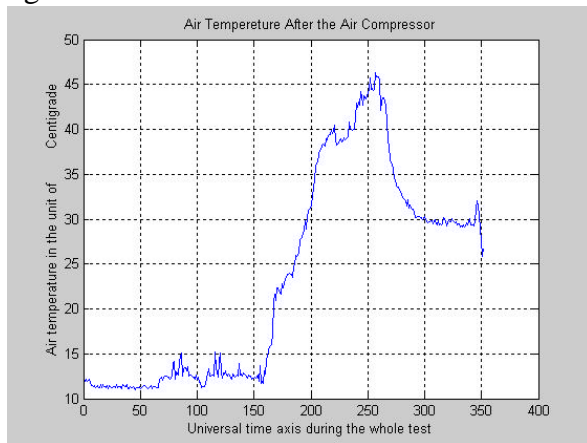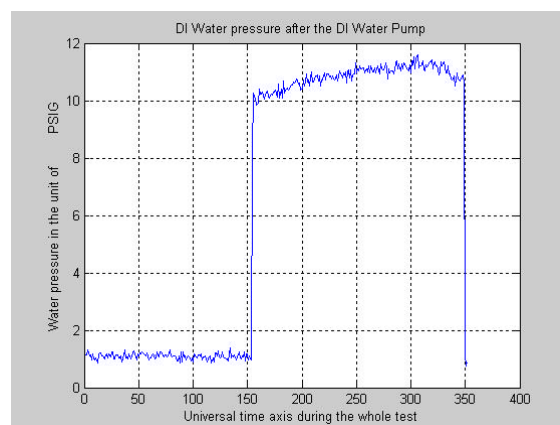

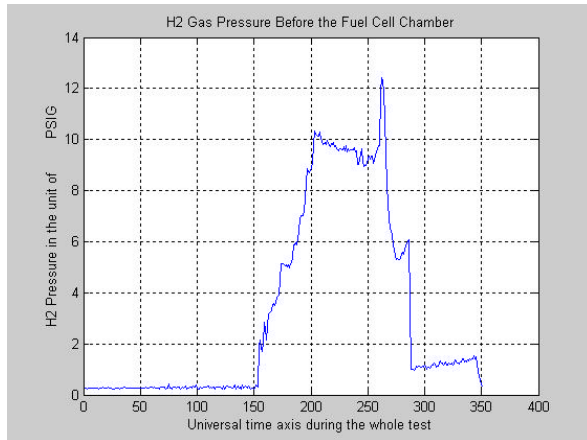Graph 1: Air Temperature
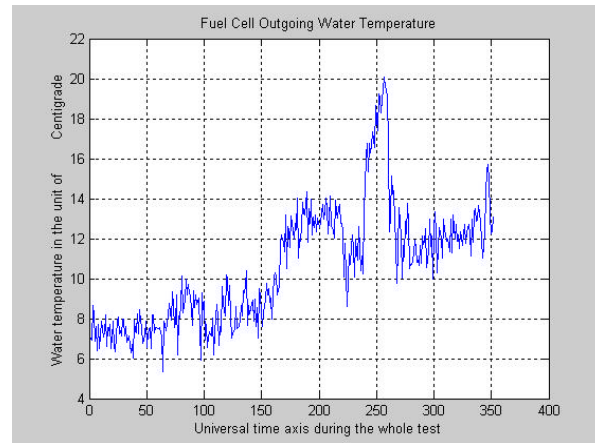
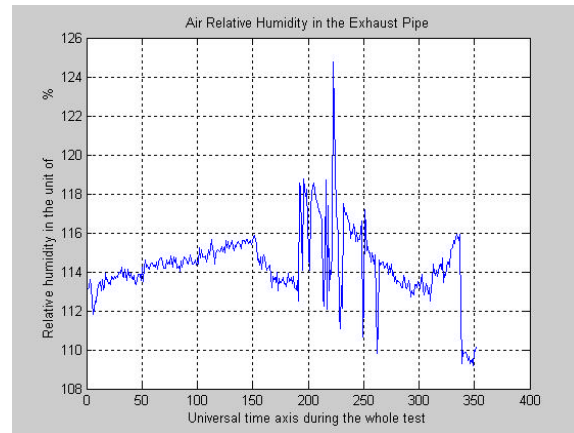Graph 2: Incoming Water Temperature
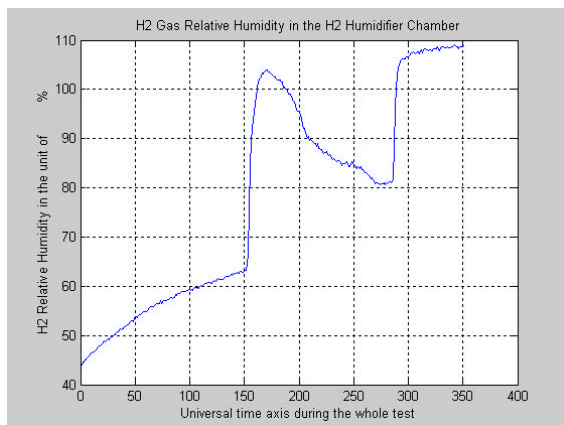

Graph 4: Air Pressure
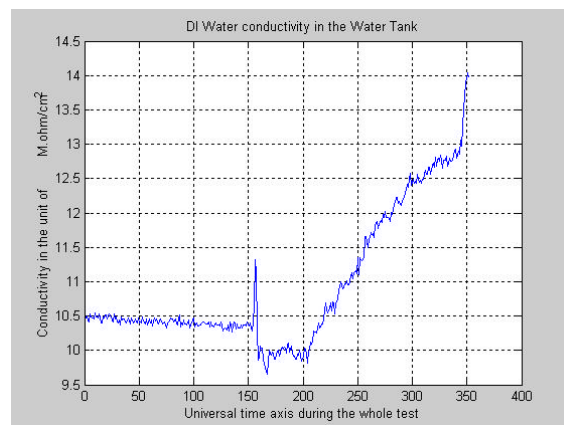

Graph 5: Water Pressure

Graph 6: Hydrogen Pressure

Graph 7: Air Humidity sensor Results

Graph 8: Hydrogen Humidity

Graph 9: De-ionized Water Conductivity

Although there are several factors that may account for the behavior of the cells, the increase in conductivity of the water indicated in the graphs is a possible problem and prevented further testing of the system until the water could be replaced.

V. Conclusion
The Texas Tech fuel cell powered SUV has been designed and built and is currently under going debug and test. The LabVIEW monitoring and control system has proven to be a versatile and powerful hardware and software combination for this complex project.

VI. Acknowledgement
The U. S. Department of Energy, General Motors, Honeywell and Quantum have provided invaluable experience for the students involved in the FutureTruck Challenge and broadened the playing field for alternative fuel and hybrid vehicles. This project was partially funded by the Texas Advance Technology Program.

REFERENCES

[1] C. Berger, Handbook of Fuel Cell Technology, Englewood Cliffs, NJ: Prentice-Hall, Inc., 1968.

[2] J. Kim, S. Supramaniam, and C. E. Chamberlin, " Modeling of Proton Exchange Membrane Fuel Cell Performance with an Empirical Equation," *Journal of the Electrochemical Society,* Vol. 142, No. 8, 1995, pp. 2670.

[3] K. R. Weisbrod, and N. E. Vanderbogh, "Effect of Operation Parameters and Anode Gas Impurities upon Polymer Electrolyte Fuel Cells," *29th Intersociety Energy Conversion Engineering Conference,* Monterey, CA, August 1994.

[4] F. Barbir, M. Fuchs, A. Husar, and J. Neutzler, "Design and Operational Characteristics of Automotive PEM Fuel Cell Stacks", *Society of Automotive Engineer,* Inc., 1998.

[5] Parten, M.E., Maxwell,T.T., et.al., "An Electrically Assisted, Hybrid Vehicle," Proceedings of IEEE Vehicular Technology Conference, Ottawa, Canada, May, 1998

[6] Parten, M.E., Maxwell,T.T., et.al., "A Combined Electrical and Mechanical Engineering Senior Design Laboratory," Proceedings of ASEE 1999 Annual Conference, Charolette, North Carolina, June 1999

[7] Parten, M.E., Maxwell,T.T., et.al., "Modeling a PEM Fuel Cell for Use in a Hybrid Electric Vehicle," Proceedings of IEEE Vehicular Technology Conference, Houston, Texas, May, 1999

[8] Parten, M.E., Maxwell,T.T., et.al., "An Intelligent Battery Management System for Electric and Hybrid Electric Vehicles," Proceedings of IEEE Vehicular Technology Conference, Houston, Texas, May, 1999

[9] Parten, M.E., Maxwell,T.T., et.al., "Advanced Vehicle Research in a Multidisciplinary Project Laboratory," Proceedings of ASEE 1998 Annual Conference, Seattle, Wa., June 1998

Micheal E. Parten

Micheal E. Parten is a Professor of Electrical Engineering at Texas Tech University. Dr. Parten has conducted research and published in the areas of instrumentation, control, modeling and simulation of a variety of systems, including hybrid electric vehicles. Dr. Parten has served for over sixteen years as the Director of the Undergraduate Laboratories in Electrical Engineering.

Timothy T. Maxwell

Timothy T. Maxwell joined the Mechanical Engineering Department faculty at Texas Tech University in 1984 and has been involved in vehicle research for over 16 years. He is presently involved in several research projects related to vehicles/engines and is co-author of a popular alternative fuels research. Dr. Maxwell has been an advisor for all the TTU teams competing in alternative fuels competitions since 1989.