Analysis and Hardware Development of a Novel Prototype Hybrid PEM Fuel Cell Li-Ion Battery Scooter

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Abstract—In this paper, an outline of a project has been covered in which a ZiP'r4 Electric Scooter was first analyzed and later converted to a hybrid PEM fuel cell - Li-ion battery powered vehicle. An automatic hybrid controller for the vehicle power management is also proposed. This design can be implemented in the longer run on general vehicles; thus creating independence from fossil fuels

***Index Terms*—Fuel cell, Li-ion battery, Hybrid-Fuel cell vehicle, Electric Scooter**

List of Symbols

To facilitate the discussion, the symbols are listed as follows:

V	Terminal voltage of fuel cell
E_{Nernst}	Open circuit voltage of fuel cell
i	Current (in amperes)
ε	Efficiency
N_{cell}	Number of cell in the stack
T_{fc}	Fuel cell initial temperature (in Kelvin)
R	Gas constant, 8.3143 j/(mol. K)
P	Pressure (in Pascal)
V	Volume (cubic meter)
M	Molar value of the gases

I. Introduction

Alternative energy solutions have a lot of attraction in today's research arena. Environmental problems and cost of oil in the last decades has led the development of Electric, Hybrid Electric and Fuel cell Vehicles. Fuel cell vehicles (FCVs) represent a radical departure from vehicles with conventional internal combustion engines. Like electric vehicles, FCVs are propelled by electric motors. But while battery electric vehicles use electricity from an external source (stored in a battery), FCVs create their own electricity [1-2]. Some fuel cell prototype vehicles have been manufactured for the purpose of research, but they are not yet in commercial stage. The main obstacles for the commercialization of fuel cell vehicles are the high cost and poor transient performance. Further, the current fuel cell system does not allow bidirectional energy flow; thus, prohibiting braking energy regeneration. Therefore, some kind of hybridization of fuel cells with other energy storage devices such as batteries and ultra capacitors will remain advantageous for a long period of time [3]. Some studies and experiments have been done involving hybrid fuel cell vehicles [4 - 6]. In [4], the requirements on energy storage devices in a fuel cell vehicle are analyzed. A midsize SUV and a midsize car are designed and simulated using ADVISOR in order to help the Freedom Car technical teams. In [5], a fuel cell system with nominal power of 48 kW is hybridized with super capacitors with a storage capacity of 0.360 kWhr. The hybrid system is then implemented on a road vehicle and tested. In [6], optimization tools are linked to ADVISOR for the optimal design of a battery fuel cell SUV. In particular, ratings of fuel cell and battery and energy management strategy are optimized to maximize fuel economy, while meeting the pre-specified vehicle performance constraints.

The current research is focused on the need for a new design for public hybrid transporters (i.e. wheel chairs, scooters, golf carts, etc.). The new design should overcome the conventional rechargeable lead-acid battery powered problems. It should be reliable and able to answer the users and the technology concerns and challenges, such as: the ability to drive the vehicle for a longer range (e.g. mileage), with the same power system without the need to recharge or refuel. The new design should also enable the power system to deliver instantaneous power for sudden acceleration and for additional power needed for vehicle auxiliaries.

These challenges can be addressed by utilizing a hybrid system combining: proton exchange membrane (PEM) fuel cell, Li-ion battery with a novel thermal management system using phase change material (PCM), and a smart control system. The battery system will provide the required power during periods of peak demand: starting-up, acceleration, and sudden load changes. On the other hand, the fuel cell will provide the power during constant speed traveling or cruising. The proposed control system will be used to handle all the power managements under different load conditions.

The project first analyzed the current wheel chair scooter and designed for similar vehicle requirements. From analysis it was determined that a 3 HP continuous electric motor could supplant the physical aspects of the current scooter. In order to

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power such a motor a 500W PEM fuel cell of Reli -on was used to provide the necessary power. The fuel cell would draw its fuel from a hydrogen cylinder located onboard. In order to assist the fuel cell with transient loading, it was determined that a battery pack would optimize the design. The batteries chosen were 4 Li-ion 16.4V 7S2P (seven cells in series and two in parallel) which are capable of discharging large amount of currents rapidly and are far lighter in weight compared to the conventional lead acid batteries. This type of behavior is ideal for congested driving that requires frequent acceleration and breakings. This novel battery pack has been developed, designed and manufactured by the Fuel cell & battery research group of Illinois Institute of Technology, Chicago's Center of Electro Chemical Science & Engg. Thus the vehicle would use the fuel cell as its primary source of power and the batteries as backup for transient power requirements, such as starting of the fuel cell, accelerating the vehicle and for driving uphill. During the normal drive the fuel cell will provide the power to the vehicle and excess energy from the fuel cell will charge the batteries. Two battery packs have been installed onboard so as to ensure continuous and smooth driving of the vehicle. A novel hybrid controller was also designed and developed by the same research group so that the battery and fuel cell interaction could be optimized. The basic research shows that there is much promise in the innovation of a Hybrid hydrogen fuel cell and Li-ion batteries based vehicle, in respect to both the environment & cost subject to mass production.

II. ZIP'R4 TRAVEL SCOOTER

The Zip'r4 travel electric scooter from Zip'r Mobility was designed and manufactured with the concept of simplicity keeping in mind the mobility of disabled people. This category also includes individual vehicles sold for personal use, getting around a neighborhood or used as shopping cart vehicles for disabled people in stores.

Electric scooters are generally not street-legal. However, when outfitted with appropriate safety features, including turn signals, headlights, and brake lights; electric scooters can meet the requirements of some localities. Fig.1 shows the urban cycle of a typical electric scooter.

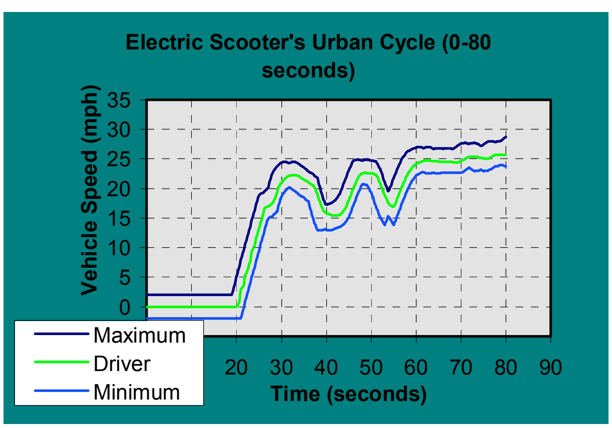

Figure 1: Electric Scooter urban cycle

A. *Specifications of ZiP'R4 Travel Scooter*

TABLE I. SPECIFICATION OF ZIP'R4 TRAVEL SCOOTER [7]

Specifications:	
Motor	155 W, 0.21 hp
Battery (Standard)	12 V, 12 Ah (x 2)
Range	Up to 10 miles per charge
Battery charger	Off board
Top Speed	4mph
Total weight	110 pounds
Dimensions:	36.4 inches (L) × 19.5 inches (W)
Ground clearance	2.1 inches
Turning Radius	38 inches

B. *Installation of the fuel cell system on the vehicle*

We decided to place the fuel cell and battery charger beneath the passenger seat. Hydrogen tank and batteries unit would be incorporated behind the seat on wooden board (later it would be in a closed box) and electric motor at its usual place. The proposed format is drawn below in Fig.3:

Figure 2: Vehicle under experimentation

III. LI-ION BATTERIES

The two primary battery competitors for use in both pure electric vehicles and hybrid-electrics are nickel metal hydride (Ni-MH) and lithium-ion (Li-ion). While Ni-MH currently has an edge over Li-ion in terms of production readiness, Li-ion has twice the energy density of Ni MH [8-10].

Lithium ion batteries have a nominal voltage of 3.6V and a typical charging voltage of 4.1V. The charging procedure is "constant current/ constant voltage" ,charging with constant current until 4.1V is reached by the cell and continuing with this constant voltage until the current drops to zero. Lithium ion batteries cannot be fast-charged and need at least 4 hours to get charged completely. One great advantage of Li-ion batteries is their low self-discharge rate of only approximately 5% per month approx compared to over 30% per month and 20% per month in nickel metal hydride batteries and nickel cadmium batteries respectively [9-10].Tble I shows the specification of 18650 Li-ion cell [9-10].

TABLE II: SPECIFICATION OF A 18650 LI-ION CELL.

Nominal voltage	3.67 V
Nominal capacity	2.0 Ah
Energy	7.34 Wh
Size	Diam: 18 mm,Length: 65 mm
Weight	42 g
Energy Density	
Gravimetric	160 W*h/kg
Volumetric	300 W*h/l
Charge duration	2-4 h (100%)
Operating Specifications	
Operating voltage	4.2-3.0 V
Charge voltage	4.2 V ± 50mV
Cut-off voltage	3.0 V
Temp. range	-20 to 60°C

The state of charge (SOC) of Li-ion batteries can also be sensed easily, so charging durations can be managed and driving ranges can be accurately predicted. Their energy efficiency and charging/discharging efficiency are high. Charging and discharging reactions produce relatively little heat, so a simple cooling system is adequate, and operation is possible in a wide range of ambient temperatures [10].

The batteries chosen were 4 Li-ion 16.4V 7S 2P. This novel battery pack has been developed, designed and manufactured by the fuel cell and battery research group of Illinois Institute of Technology, Chicago's Center of Electro Chemical Science & Engineering.

IV. HYDROGEN FUEL CELL

There is an increasing interest in the use of Proton Exchange membrane (PEM) fuel cells for both mobile and stationary applications as environmentally friendly power source. Emphasis is placed on high power density with adequate energy conversion efficiency for mobile applications and on high energy efficiency with adequate power density for stationary applications. Two key issues limiting the widespread commercialization of fuel cell technology are better performance and lower cost. Major operating parameters include cell temperature, pressure, reactant stoichiometry and gas stream composition [11].

PEM fuel cells are compact and capable of powerful electric current relative to their sizes. They use a solid polymer membrane as an electrolyte. This immobilized electrolyte simplifies the sealing in the production process, reduces corrosion and provides for longer cell and stack life [12]. PEM fuel cells also operate at low temperature, less than 100 degrees Celsius, allowing faster start-ups and immediate responses to changes in the demand for power.

For the purpose of our research, one of our sponsors, Avista Labs donated us a fuel cell: The *Independence 500.* This fuel cell runs on pure hydrogen gas and air. The fuel is designed for stationery battery charging applications. The output of the fuel cell is 52 volts constant and a maximum current output of 10 amps (thus about 500 watts power output). It also has a second voltage output: a varying voltage between 51-55 volts.

However, the fuel cell has a drawback. It needs an external power source to start operating and an external source voltage of 35-40 volts initially to start operation. But once it is turned on, this external source can be removed.

The fuel cell produces energy based on the reduction reaction of hydrogen, which in turn reacts with oxygen from air to produce water vapor. Electricity thus is produced directly without the need of any generator. However, conversion circuitry is needed within the fuel cell to convert this power to a steady electric supply that can be used reliably for different applications. The electricity production process is very efficient depending on the membrane used, typically 30-40%, while some fuel cells that re-use waste heat energy of the chemical process, have up to 80% efficiency.

The amount of hydrogen can be determined for a given power and voltage specification. For example, the fuel cell provides 500 watts of power with a total voltage of 48 V. Since the fuel cell operates at 35% efficiency at full load, the current, *i*, and the amount of hydrogen required can be determined.

$$i = \frac{P}{V} = \frac{1000}{48} = 20.83 Amp$$

$$M_{H2} = 20.83 Amp * \frac{3.76*10^{-5}\, kgH_2}{hr*Amp} = 7.832*10^{-4} \frac{kgH_2}{hr}$$

$$\varepsilon = \frac{U_{Consumed}}{U_{Feed}} \rightarrow 0.35 = \frac{7.832*10^{-4} \frac{kgH_2}{hr}}{U_{Feed}} \rightarrow U_{Feed} = 0.0022 \frac{kgH_2}{hr}$$

The efficiency value was determined by specifications from the fuel cell manufacturer and no information was found in regards to the fuel cell efficiency at different operating conditions. Using the stated conditions and stoichiometry, equivalent amounts of air in the feed can be determined. It is assumed that air consists of 20.9% oxygen and 79.1% nitrogen. Based on the storage conditions, the volume of hydrogen and air can also be determined by the Gas law and appropriate correlations. All values are based on specifications of the fuel cell.

The fuel cell performance was also evaluated through the Simulink modeling of the Avista 500 W fuel cell. The model reported in [13-14] was used for analyzing the different parameters of the fuel cell. A constant channel pressure with non- controllable input fuel flow into the fuel cell has been considered for this model. The Channel pressure will be kept constant by the adjustment of input fuel flow through fuel cell stacks according to its load current [13-14].

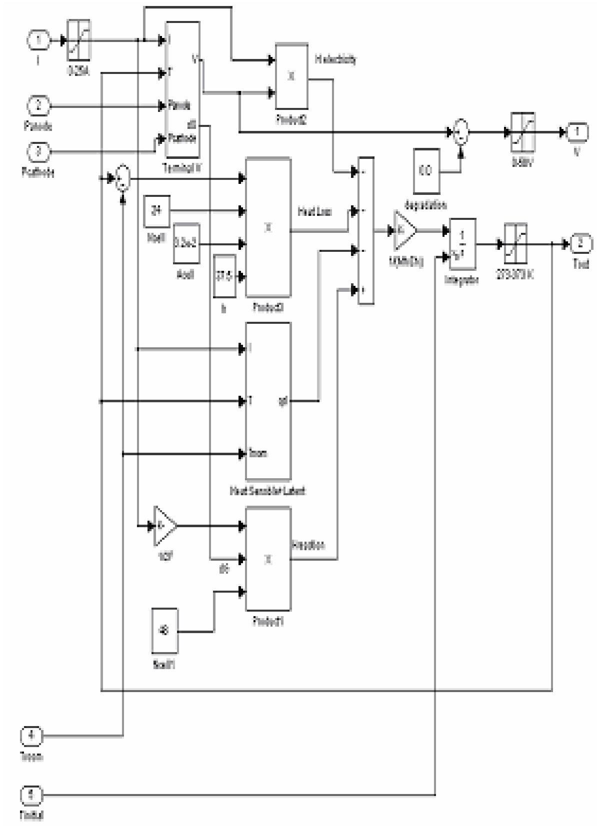

Figure 3: Simulink model of the Avista 500 W fuel cell.

A. Parameters in the model

1. N cell: Number Of Cartridge * 2 = 12 * 2 = 24
2. A cell: Area of each Cartridge ~ 320 cm^2
3. Pressure : set as 37.5 $W/(m^2*K)$
4. The output current range I: 0-25A
5. I_{rated}=20A, I_{limit}=25A
6. Nominal output voltage: 24V

The output voltage can not be over 58 V (NcellE_o)*
The output temperature can not exceed 100 C (373K)

B. Simulation:

Simulation has been carried out for different timing intervals Simulation results for T = 3600 seconds (1 hour) are shown in Figures 4 -7. The output current is significantly increasing. However as per the range of current of this fuel cell it should not exceed 25 A. Output voltage is constant for few minutes and it starts decreasing gradually The temperature of Fuel cell is increasing linearly with time, however remains under the safe range and the observed pressure was increasing linearly to an approx value of 315 atmospheric pressure.

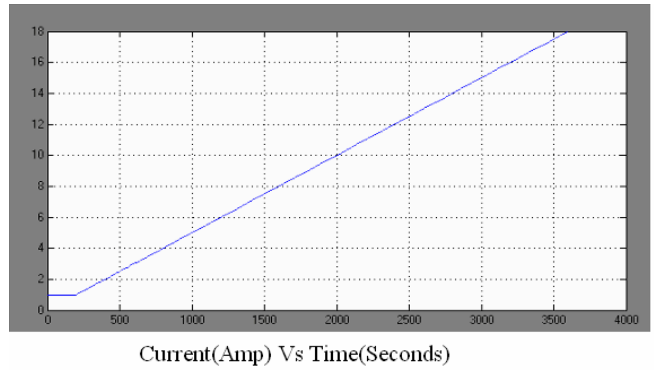

Figure 4: Output current of the fuel cell Vs time.

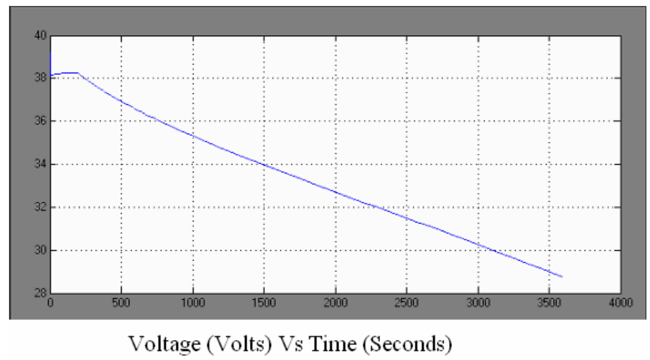

Figure 5. Output Voltage of the fuel cell Vs time.

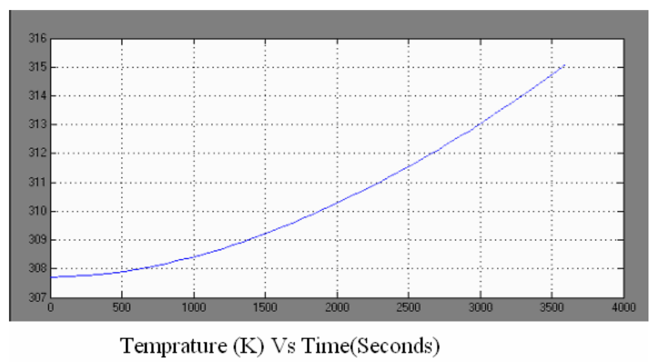

Figure 6: Temperature of the fuel cell during operating condition.

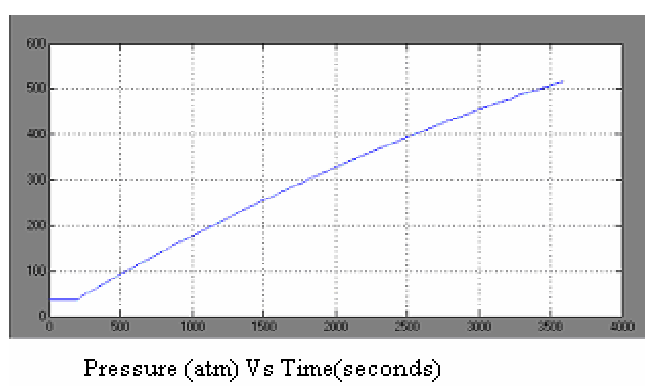

Figure 7: Observed Pressure Vs time.

V. Hybrid Vehicle:

A. *Vehicle Components*

The main Components of the prototype Hybrid Vehicle are:

1. Fuel Cell
2. Hydrogen Tank
3. Lithium Ion Battery Block
4. Charger Unit
5. Electric Motor
6. Hybrid Controller Unit

We have discussed the first four components in the previous sections. A brief overview of the electric motor and the hybrid controller unit is given below.

B. *Electric Motor*

The same motor has been used supplied by the manufacturer with the vehicle. The motor on average requires 275-300 Watts of power, i.e. when it is running at a constant speed. However, occasionally, it requires more power, up to a kilowatt, like when accelerating from a stop, or when cruising up an incline. When the electric motor starts, it requires a large amount of current to get the motor rotating. This current value is up to 60 amps when the motor is supplied with 32volts. Fortunately, this spike lasts only for a few milliseconds. The motor needs to be supplied with at least 24 volts.

C. *Hybrid Controller*

1) *Assessing the Challenge*

Today's typical automotive design flow incorporates a series of distinct stages. The initial phase includes the functional specification and system design, followed by the specification and design of all components in consultation with suppliers. Moving into the prototype stage, components are tested and verified against specification. However, it is not until the full system integration and verification phase, when physical components are connected for the first time, that any problems arising from the functional specification and system design stages become apparent. Virtual system verification removes this risk, and enables better testing of choices, such as choosing optimal system architecture or choosing between components offered by two different vendors. Using simulation, problems in a functional specification and in design choices can be resolved much earlier in the process and prior to the actual prototype build [8]. Figure 8 shows the proposed block diagram of the Controller.

2) *Functioning of the proposed circuitry*

The battery system will provide the required power during periods of peak demands: starting-up, acceleration, and sudden load changes. On the other hand, the fuel cell will provide the power during constant speed traveling or cruising. The nature of the circuit is designed in such a way, so that when one battery block is being charged, another battery block will discharge. The switches used are bi directional Photo-Voltaic Switches from International rectifier [15]. The proposed control system will be used to handle all the power managements under different load conditions as follows:

Initially battery is directly used to start fuel cell. When motor is started, it draws high starting current rising steadily from zero and reaches to several times rated current. Initially, it comes from fuel cell for very short period of time through SW1. However, the moment it crosses the maximum limit of the fuel cell current (say 2A), V*I becomes higher than V_{set}. The op amp based comparator goes to a high level. It conducts LED of SW_2. Thus SW_1 turns off. Control circuit common terminal is connected at the battery source only. As soon as the vehicle operates in normal cruising condition, LED of switch SW_1 turns on and SW_2 turns off. If the output power of the fuel cell is more than the consumed power by the motor, op-amp based comparator again come into action and switch on the close switch so as to utilize that extra power for the charging of the batteries.

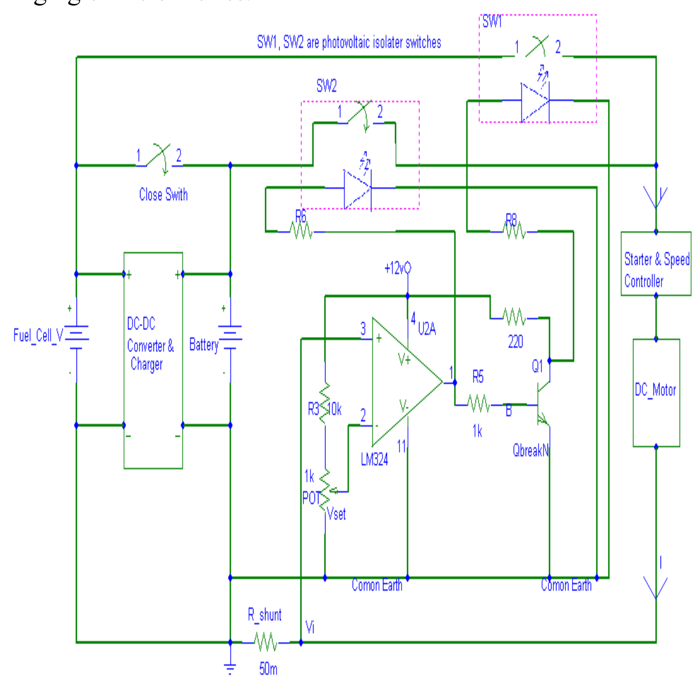

Figure 8: Proposed block diagram of hybrid controller

VI. Experiments & Observations

A. *Phases in the HEV Project*

Initially, Lead Acid Batteries of the scooter were replaced with the novel Lithium ion Battery packs and the performance was evaluated and results were quite promising. In the Second phase, Fuel Cell was integrated in the vehicular system to charge the Lithium Ion Battery Packs while the battery packs power the Scooter. During the third phase the scooter was tested as a hybrid vehicle with the Fuel Cell as the primary source and using the Li-ion battery packs as the backup power source. The overall power management during this phase was based on manual switching. In the ongoing final phase the vehicle will be tested as the hybrid system with hybrid controller based on voltage and current conditions.

B. *Observations till Third Phase*

The nature of the circuit is designed in such a way, so that when one battery block (block I) is charging another battery block (block II) will discharge. With the activation of synchronized relays, battery block II will charge and battery block I will discharge. For additional amperage to the motor another switch is available to route fuel cell power that has been stepped down to 24.5 volts. In addition to the permanent charger connections, the 24.5 volts of fuel cell power can be routed in parallel to the motor (and relay selected discharging battery) or to an external load device. 24.5 volts is always delivered to the charging portion of the circuit via chargers. Due to relay design the charging portion of the circuit is broken up into individual 3s (three cells in series)and 4s connections perfect, for background charging. When the above mentioned relay is activated, the current charging battery block will go into discharge mode by connecting 4s and 3s together to make 7s. This 7s battery power is then fed to the motor (with the option of having converted 24.5 volts in parallel to battery output).

As for the pressure of Hydrogen is concerned, a good level is below ~15-20 psi with the middle dial, and 1 or 2 full turns of tank dial, and fuel cell dial. To start the fuel cell, one needs to have the correct pressure and activate the battery pack inside the fuel cell to start the electrolyzing processes.

Result from test drives around university campus, showed that with fully charged battery packs the vehicle moved at a substantial speed and with a satisfactory magnitude of torque. It was noted that when fuel cell power was added, additional power was delivered to the motor, and also additional voltage/speed was recorded. It was also observed that with low charged batteries, the fuel indicator lights turned dim but the vehicle did not budge. With added fuel cell power, the motor moved with satisfactory power and speed, but additional hydrogen was consumed in the process. While the vehicle is running on low batteries, the fuel cell power was also charging the battery pack slowly, showing the effectiveness of background charging.

VII. Further Milestone

The basic research shows that there is much promise in creating a hydrogen fuel cell vehicle, in respect to both the environment and cost subject to commercial production. This project has covered much of the preliminary research, design aspects and has made progress towards the objective. However, there is still much work to be done; both in the validation of the hybrid Control system and the component selection, as it would simplify the optimization of the design and allow for automatic switching based on voltage and current conditions.

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