Performance evaluation of fuel cell-battery hybrid electric vehicle

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PERFORMANCE EVALUATION OF FUEL CELL-BATTERY HYBRID ELECTRIC VEHICLE

by

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Bachelor of Science
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1999

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Electrical Engineering
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ABSTRACT

Performance Evaluation of Fuel Cell-Battery Hybrid Electric Vehicle

by

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Hybrid electric vehicles that utilize gasoline-powered engines as a base source of power enjoy widespread customer acceptance because of their performance and economy. However, the future generation of these vehicles as well as conventional ones will have to move away from internal combustion engines due to depleting fossil fuel reserves and stricter environmental norms. Hybrid power sources composed of fuel cells and deep cycle batteries combine the high energy density of fuel cells with the high power density of batteries, offering efficient transportation without harmful emissions. This thesis describes the conversion of an electric vehicle into a hybrid fuel cell – battery vehicle and adds to the growing body of studies paving the way to a conversion to a hydrogen economy.

The original all electric vehicle was powered by twelve 6 V batteries, each rated at 244 Ah (@ C/20). The 72 V source supplies an 11.5 hp series excited DC motor through a solid-state speed controller. The controller is a step-down (or buck) DC-to-DC converter in which the duty ratio of the power transistor is controlled by the position of the “gas” pedal. The dual power source of the modified vehicle consists of a 5.5 kW fuel
cell and six 12 V batteries, each rated at 145 Ah (also @ C/20). A DC-DC power converter is placed between the fuel cell and the battery bank to regulate the fuel cell source voltage, and to control the power supplied from the fuel cell and the batteries under different load conditions.

Since the 5.5kW fuel cell cannot handle peak power demand alone, it is ideal to have the fuel cell provide base power up to 5.5kW and let the battery bank act as a peaking unit, providing all power past that level. This thesis contains experimental results showing this configuration.
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CHAPTER 1

INTRODUCTION

This thesis describes the conversion of a battery electric vehicle into a hybrid fuel cell – battery electric vehicle and adds to the growing body of studies paving the way to a conversion to a hydrogen economy.

There is a historical trend to move from fuels based in carbon to fuels based in hydrogen [1]. This trend starts with wood (which releases significant carbon dioxide emissions), then proceeds through coal, petroleum, natural gas, and ends in hydrogen (which releases no carbon dioxide emissions). America’s increasing need for petroleum for transportation consumption indicates a need to expedite transition to hydrogen. Currently consumption of petroleum continues to rise while domestic production remains constant.
Fuel cells do not burn hydrogen. A hydrogen proton electron membrane (PEM) fuel cell is an electrochemical device that consists of two electrodes sandwiched around a negatively charged electrically conductive material called an electron membrane [3, 4]. Hydrogen fuel is fed to the anode while oxygen passes over the cathode as shown in the following figure. Encouraged by a catalyst, usually platinum, the hydrogen atom splits into a proton and an electron. The proton can pass through the electron membrane to reach the cathode, but the electron cannot because the membrane is negatively charged. The electron must go through an external circuit containing a load which consumes the power generated by the cell. Each cell produces a voltage of 0.7V, and high voltages are achieved by connecting many fuel cells in series, called a fuel cell stack.
Fuel cells offer a quiet, zero emission way to power automobiles that reduces dependence on foreign petroleum. The only byproduct of the process is the formation of pure water created from the hydrogen’s exposure to air. Fuel cells have very few moving parts which keeps maintenance costs low. All of the major automobile manufacturers are developing fuel cell vehicles because of these advantages, but the concept of fuel cells is not new.

Fuel cells were invented in 1839, but the prohibitive cost of manufacturing fuel cells and the lack of a widespread infrastructure for storing, distributing, and utilizing hydrogen held the technology back. The term “hydrogen economy”, used to describe a system where hydrogen would be readily stored and available for mass consumption, became a buzzword in the early 1970s when the price of crude oil increased and there...
was a scramble to find a secure energy source. However, as tensions lessened in the Middle East and crude oil prices fell back down, the term "hydrogen economy" all but disappeared. Petroleum has continued to be the fuel of choice for the transportation sector worldwide, but recently the term "hydrogen economy" has resurfaced due to further stability issues in the Middle East. For fuel cell vehicle technology to become widespread, the fuel cell system must have weight, power density, startup, and transient response similar to present day internal combustion engine based vehicles. [6]

Hydrogen fuel cells seem like an easy solution to energy problems because hydrogen (H\textsubscript{2}) is the most abundant element in the universe. The problem is that practically all of it is found in combination with other elements such as water (H\textsubscript{2}O) or fossil fuels such as natural gas (CH\textsubscript{4}). The processes used to remove hydrogen from fossil fuels or water consume energy. Removing hydrogen from fossil fuels can still release carbon dioxide into the atmosphere. Removing hydrogen from water, through electrolysis, can be done using electricity from fossil fuel combustion or renewable sources. If electrolysis became a widespread technology available at homes or in vehicles, then the amount of hydrogen needed from a hydrogen infrastructure would be less.

A primary concern of this project was discovering what sorts of power control strategies were appropriate in the project vehicle. The Nuvera fuel cell purchased provides regulated 48V output, which is boosted to 72V through a DC-DC converter to match the voltage of the vehicle and the battery bank. However, the fuel cell is rated at only 5.5kW and the electric vehicle could require double that at times. The battery bank must be intelligently introduced into the system so that enough energy is available to the vehicle at all times.
All fuels, such as gasoline, are potentially dangerous, but hydrogen fuel has a reputation of being unsafe. Hydrogen vehicles and the supporting infrastructure can be engineered to be as safe as existing gasoline systems. Proper engineering, education, and common sense reduce the risk in any potentially explosive situation. Dealing with the perception and reality of hydrogen safety will be critical to the successful wide introduction of hydrogen into our energy economy.
CHAPTER 2

REVIEW OF RELATED LITERATURE

As political pressure to discover cleaner and less foreign dependant forms of energy increases, more and more academic study is being done on using fuel cells in transportation.

Most control strategies for hybrid fuel cell-battery electric vehicles consider fuel cells where the output is not regulated, and as the demand for load current on the fuel cell increases, the voltage output of the fuel cell decreases. The challenge of dealing with an unregulated fuel cell is figuring out how to manage a variable-voltage DC source in a fixed-voltage AC world [7]. For instance, one paper [8] investigates how to get optimum fuel cell optimization using multilevel inverters. It notes that the reduction of the fuel cell output voltage between full load and no load is about 30%. Given the reduced utilization factor of the fuel cells at low loads, the paper proposes a level reduction control technique for a seven layered inverter using sine triangle wave comparison to address the problem. This is just one way that unregulated fuel cells are being studied.

A power flow control system can be microprocessor controlled. By identifying different regions of operation, such as constant fuel cell current mode, constant battery current mode, constant battery voltage mode, and load disconnection, and providing input data such as existing currents and voltages, algorithms can be programmed into the microprocessor to control switching between the different modes as needed [9]. The following figure illustrates a possible control scheme using those modes.
States:
CFCC: Constant Fuel Cell Current mode
CBC: Constant Battery Current mode
CBV: Constant Battery Voltage mode
DISC: Disconnection of the load

Conditions of Events:
1: Power on
2: $I_b > I_{ref}$
3: $I_b > I_{med}$
4: $V_b > V_{ref}$
5: $V_b < V_{ref}$, $I_b > I_{ref}$ (This rarely happens)
6: $I_b > I_{med}$
7: $V_b > V_{ref}$
8, 9, 10: $|I_b| > I_{dwc}$ (for instance, $I_{dwc} = 4 \times I_{ref}$. This happens under very heavy load)

Figure 3 Example State Machine Representation of the Control Strategy for Active Hybrid Fuel Cell/Battery Power Sources

An undergraduate project concerning a hybrid electric "go cart" uses a programmed microcontroller, but ultimately fails because the fuel cell could not produce a voltage high enough to supply the needs of the circuit [10]. When the batteries of the vehicle
need charging and the vehicle is being driven, it is important to protect the fuel cell from a current demand beyond what it can handle.

An interesting way to invert the DC output of a fuel cell into AC power is to use many fuel cell units not simply connected in series, but connected so that fuel cells can be turned on and off as needed. This approach is proposed for applications such as buildings where the load varies throughout the day [11]. This multilevel approach is shown in the following figure.

Figure 4 Multilevel DC-DC Converter Connected to a Three-Phase Inverter
There are many approaches to modeling fuel cells and fuel cell vehicles. Many of them use ADVISOR, a licensed software package that was formerly free. Some models take into account the transmission, vehicle dynamics, induction machine, field oriented controller, and the power electronics drive, and more to model vehicle performance [12]. A complete thermodynamic and mechanical model of the vehicle can be quite complicated as is shown in the following figure.

One such paper [14] describes a novel method for simulating this characteristic of fuel cells in P-Spice by manipulating a transistor model’s characteristics. The three regions of the resulting current to voltage curve are activation polarization, ohmic
polarization, and concentration polarization. The activation loss is dominant at low levels of load current where the rate of the electrochemical reaction at an electrode's surface is controlled by sluggish electrode kinetics. The ohmic loss is dominant at moderate levels of load current and is due to the resistance of the polymer electrolyte membrane to the ions and the resistance of imperfect electrodes. The concentration loss is dominant at high load currents and relates to the change in the concentration of the reactants at the surface of the electrodes as the hydrogen is used. The diode is used to model both the activation and the ohmic losses, while two BJTs are used to model the mass transport losses.

![Figure 6 Schematic for Novel P-Spice Fuel Cell Model](image)

These three regions are illustrated in the following figure. The figure also shows that higher pressure and temperature can increase the fuel cell voltage.
Figure 7 Usual Voltage-Current Characteristics of Fuel Cells [15]

Another paper [16] uses formulas describing the gas diffusion in the electrodes, material conservation equations, fuel cell output voltage, and energy balance of the thermodynamics to build a SIMULINK model of an unregulated fuel cell. Another
approach is to build P-Spice models that reflect the electrochemical reactions in the fuel cell [17] using data such as pressures at the anode and cathode, operating temperature, cell impedance, cell electrical capacitance, and other such information.

There are different types of fuel cell vehicles [18]. A non-hybrid fuel cell vehicle (FCV) is powered by only a fuel cell. Semi-hybrid FCVs and hybrid FCVs are powered by both a fuel cell and an energy storage system such as a battery bank. A semi-hybrid FCV uses the energy storage system to support the output power of the fuel cell, while a fully hybrid FCV does that and is able to absorb regenerative energy. If that terminology were applied to this thesis’s project, the FCV is a semi-hybrid FCV system. Though a semi-hybrid FCV cannot capture regenerative energy, it does offer reduced complexity of power electronic devices and controls required for regeneration.

Figure 8 Different Fuel Cell Vehicle Configurations

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Another paper explains different structures of hybrid electric vehicles [19, 20, 21, 22]. In a parallel hybrid, multiple power sources power different drivshafts. Each drivshaft has to be associated with an energy source. In a series hybrid, the on-board total energy source results from the combination of two or more energy sources. Another possibility is a combined hybrid which would use multiple drivshafts powered serially. Since the project's vehicle has only one drivshaft, a series hybrid system was built.

![Diagram of a typical series hybrid fuel cell based vehicular drive train](image)

Figure 9 Typical Series Hybrid Fuel Cell Based Vehicular Drive Train [19]

The simplest hybrid configuration results by connecting both the fuel cell and the battery directly to the power bus. A disadvantage of this passive hybrid configuration is that the maximum output current of the hybrid system might be limited by the current capacity of the fuel cell. By adding a DC-DC power converter between the fuel cell and the battery the configuration is changed into an active hybrid configuration. The DC-DC power converter is required to balance the power flow between the fuel cell and the battery to satisfy the load power requirements [9].
Hybrid vehicles can use supercapacitors in their systems as well. Supercapacitors are better than batteries at capturing and supplying short bursts of power due to their higher power density limits and their ability to charge and discharge quickly. [23, 24] The ability of the supercapacitors to store short bursts of power makes the vehicle able to recover some losses during braking, which is known as regenerative braking.

Some researchers have questioned the need for hybridization in fuel cell vehicles [25]. This paper shows that in some realistic driving conditions the addition of batteries can even create a fuel economy penalty. Without regenerative breaking, this could be even worse. However, the purchased fuel cell is rated at 5.5kW and the vehicle occasionally demands more power than that, so the choice of a hybrid scheme is fixed.

A major consideration when looking at fuel cell vehicles is where drivers will obtain the hydrogen. Some researchers point out that a wide scale use of hybrid fuel cell vehicles will not occur until a hydrogen infrastructure is present [26]. Ideally, renewable power sources such as wind or solar could be used to collect the hydrogen from water. If these systems are connected to a grid system, the energy produced by the renewable sources not needed by the grid can be stored in hydrogen for later automotive or utility use.

Fuel cells could provide reductions in energy uses and emissions. The Fuel Cell Report to Congress, 2003 [2], identifies four phases for introducing hydrogen fuel cells into wide use. This project fits neatly into phase 2. The first phase is “technical feasibility”, which lasted from 2000 to 2004. In this time they tested FC vehicle performance and feasibility using trucked in liquid hydrogen. The second phase is “controlled fleet test and evaluation” from 2004 to 2009. In this phase the use of fuel cell
vehicles is evaluated under real world conditions using hydrogen from renewable and fossil fuels. The third phase is “commercial readiness demonstrations” from 2009 to 2015. In this phase fuel cell fleet are demonstrated as commercially viable using hydrogen sources most cost effective per region. The final phase is “commercialization phase” from 2015 onward. This phase should see investment for substantial numbers of hydrogen fuel stations and fuel cell vehicle manufacturing.

There are other fuel cell options besides the PEM fuel cell [27]. Alkaline fuel cells (AFC) use an alkaline and have high performance due to fast internal chemical reactions. They were first used by NASA to produce water and electricity for astronauts. However, AFCs can be contaminated by a slight exposure to carbon dioxide. Phosphoric-acid fuel cells (PAFC) are typically used for stationary power generation, but are heavy and only slightly more efficient than combustion-based power plants. Solid oxide fuel cells (SOFC) do not have expensive platinum plate arrangement concerns that other fuel cells do because SOFCs are solid. But SOFCs operate at extremely high temperatures (around 1000 degrees Celsius) and take a long time to startup. Molten carbonate fuel cells (MCFC) operate at high temperatures (around 650 degrees Celsius), are efficient, and can convert fuels to hydrogen internally using the high temperature in a process called internal reforming. The durability and longevity of MCFCs is shortened due to component breakdown and corrosion.
CHAPTER 3

COMPONENT SPECIFICATIONS

This chapter briefly discusses the configuration of the vehicle and the specifications of each component. The hybrid fuel cell electric vehicle is comprised of a battery bank, a fuel cell, a DC to DC converter, a motor controller, and a motor. The following figure shows a simple power flow path of a hybrid vehicle.

![Figure 10 Block Diagram of Vehicle Power Flow](image)

The system integration of the system is in the following figure, showing more detail about how parts are connected.
This thesis will later describe the control circuitry between the fuel cell and the DC-DC converter. It is crucial to this project that the fuel cell is protected from seeing a load greater than 2.5kW during its warmup phase, and then can supply its full 5.5kW power once it reaches its power on demand phase. Battery current and voltage is collected and sent to a meter in the dash. The dash of the vehicle also has a data line from the fuel cell containing a variety of data including its output current.

The following photo shows the major components installed in the vehicle.
Figure 12 Fuel Cell Vehicle
Battery Bank

The existing bank of twelve 6 volt batteries (model US-2200) was replaced with six 12 volt batteries (model EV-145) from US Battery. This new battery bank weighs less (from 756 pounds to 522 pounds) and frees up space for the installation of the fuel cell. There is less capacity in the new battery bank. At 20 hours, a single US-2200 battery is rated 225 amp-hours, while a EV-145 battery is rated 145 amp-hours. The total battery capacity in the old bank is 16.20 kilowatt-hours (225 amp hours * 6 volts * 12 batteries) while the total battery capacity in the new bank is 10.44 kilo-watt hours (145 amp hours * 12 volts * 6 batteries). The 5.76 kilowatt-hour loss in battery capacity is offset by the addition of the fuel cell.

The maximum capacity of the battery varies mostly between 100 and 150 ampere-hours based on the time interval in hours. The time it takes to discharge the batteries depends heavily on the discharge current of the batteries. The two graphs below show these relationships based on data from US Battery.

<table>
<thead>
<tr>
<th>Discharge Current (Amps)</th>
<th>Discharge Time (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1630</td>
</tr>
<tr>
<td>10</td>
<td>814</td>
</tr>
<tr>
<td>15</td>
<td>500</td>
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<tr>
<td>20</td>
<td>353</td>
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<td>100</td>
<td>50</td>
</tr>
<tr>
<td>125</td>
<td>38</td>
</tr>
</tbody>
</table>

Table 1 Discharge Time of EV-145 Battery from Manufacturer Data
For modeling purposes, the internal resistance of the battery bank is needed. This can be calculated by the following formula:

\[ R_b = \frac{V_s - V}{I} \]  

(1)

Where:

- \( R_b \) is the internal resistance of the battery
- \( V_s \) is the battery voltage without a load (the open circuit voltage)
- \( V \) is the battery voltage with a load
- \( I \) is the total current supplied by the battery
$V_S$ was measured to be 73.2 volts. Different values of $V$ were gathered at different currents $I$ as shown in the following graph. Using formula (1), the average internal battery resistance of the battery bank is 0.1 ohms. Below, the marked line indicates collected data and the solid line is the line of best fit.

![Graph showing V-I Characteristic of the New Battery Bank](image)

Figure 14 V-I Characteristic of the New Battery Bank

When looking at the discharging of the batteries, Peukert’s Equation explains that discharging a battery bank at higher rates actually removes more power from the battery than a simple calculation would show it to do [29]. For example, discharging a battery with a constant current load of 10 amps does not remove twice as much power as discharging it at 5 amps, but actually removes slightly more than that. Therefore a 100 amp hour battery (at the 20hr rating) could provide 5 amps for 20 hours, but it could not
provide 10 amps for 10 hours. The available time would actually be slightly less.

Peukert's Law is usually written as:

\[ I^n \times T = C \]  

(2)

Where:

- \( I \) is the discharge current in amps
- \( T \) is the time in hours
- \( C \) is the capacity of the battery in amp hours
- \( n \) is Peukert's exponent for the battery type which can change with vehicle age

The idea is that the time (T) that a certain battery can run a certain load for can be calculated by rearranging the equation to read \( T = C/I^n \).

The internal resistance of the battery bank, or more specifically its effect on the battery voltage, can vary based on state of charge of the battery and whether the battery is being charged or discharged, as illustrated by the following two figures.
Figure 15 Battery State of Charge vs. Voltage during Discharge [29]
Figure 16 Battery State of Charge vs. Voltage during Charge [29]
Fuel Cell

Generally, a fuel cell is a stack of many cells, each one containing a negatively charged membrane which allows hydrogen nuclei to pass through them, but forcing the electrons to move through a useful circuit, creating power. The Nuvera H2e Power Module Fuel Cell has the following specifications:

- DC power output: 2.5kW to 5.5kW and idle
- DC power type: Regulated 48VDC +/- 5% at 115A (This output is the input of the DC-DC converter discussed in the next chapter.)
- DC power input: 48V DC input for startup and shutdown
- Operating Modes: Load following from 2.5kW to 5.5kW in much less than 1 second (near-instantaneous)
- Start-up time at 10 degrees Celsius: 12 seconds to 2.5kW output, and 12 minutes to full 5.5kW output
- Exhaust emissions: Water

The fuel cell has a CAN data output which can be used to monitor and/or record data on the fuel cell performance including voltage at the terminals before the internal regulator, control signals, output current, and performance of the best and worst cell in the cell stack. The CAN port, along with bundled software, allows live monitoring of the fuel cell as seen in the following figure.
The following figure is a block diagram of the fuel cell control system including the CAN line. The figure also shows how the GenlO unit monitors the output current of the fuel cell and controls the 48V DC converter. The internal supplies of the fuel cell rely on an external 48V power supply until the system is activated at the 48V converter is available.
In the project vehicle, glimpses of the activation and ohmic polarization regions at the fuel cell terminals themselves can be seen before its internal 48V regulator in the following figure. The marks indicate collected data, and the solid line shows the line of best fit.
The voltage output of the fuel cell past the internal 48V regulator was measured and is shown in the following graph.

Figure 19 Observed Voltage vs. Current before the Internal 48V DC Regulator

Figure 20 Observed Voltage vs. Current after the Internal 48V DC Regulator
This data is similar to the data provided by the manufacturer in the following figure.

Figure 21 Manufacturer Data of Voltage vs. Current Characteristic of the Fuel Cell Before and After the Internal 48V DC Regulator

However, with the DC converter in combination with the fuel cell’s dynamic response to the load there will always be a fixed output voltage from the fuel cell system, shown in the previous figure as 48 Vdc regulated, so a fuel cell model is not needed.

Starting up the fuel cell is done by first turning on the CAN enable switch which powers the internal electronics, and then turning the front panel switch to begin the fuel cell operation.
DC-DC Converter

A 48V to 72V DC to DC converter from Zahn Electronics was purchased for the fuel cell vehicle. The output of the fuel cell unit purchased is regulated at 48V, but the electric vehicle is configured to run using a 72V input. The converter is a 2 quadrant, crystal controlled, double half H bridge, interlaced, boost converter with two external inductors. The switching frequency of the unit is 31.25 kHz.

A microcontroller controls the output using two interlaced pulse width modulation signals. At a 50% duty cycle, the two signals are square waves completely out of phase so that the current and voltage ripples are zero. At other duty cycles, the square waves overlap in a manner depending on the duty cycle.

![Figure 22 DC-DC Converter Installation Wiring](image)
The installation wiring from the manufacturer does not show the logic of how the device works, but knowing that there are four switches and that current only flows from the low side to the high side suggests that this is a full bridge DC-DC converter using pulse width modulation with unipolar voltage switching.

![Diagram of DC-DC Full Bridge Converter](image)

Figure 23 Typical DC-DC Full Bridge Converter [30]

The output voltage, $V_O$, is equal to $V_A - V_B$. The four switches are $T_{A+}$, $T_{A-}$, $T_{B+}$, and $T_{B-}$. $T_{A+}$ and $T_{A-}$ cannot be on simultaneously or there would be a short. The same is true for $T_{B+}$ and $T_{B-}$. GB1 and GB2 represent control signals which are calculated from the sawtooth control signal.

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As the duty cycle $D$ is manipulated, the output voltage is changed to something higher or equal to the input voltage. If the $V_{\text{control}}$ is raised so that the sawtooth wave never reaches it, the switches are configured so that $V_{O}$ would be maximum. If $V_{\text{control}}$ is lowered, then $V_{O}$ will alternate in pulses, lowering with $V_{\text{control}}$ until the $V_{O}$ equals zero.

The desired output level of 72V is controlled by a reference voltage which is usually 5 volts. By adding a control signal as the reference voltage, the output of the converter can be lowered to voltages under 72V, which is a useful feature for adding an active control scheme to the vehicle.

Motor Controller and Motor

The Curtis PMC 1209 motor controller manages the current load drawn by the series motor based on the gear, gas pedal, and brake pedal of the vehicle. An array of paralleled power MOSFETs switches pulses of current from the fuel cell and batteries to the motor. During the interval when the MOSFETs are off, the motor current continues to flow in the freewheel diode shown below. The transistors are turned off and on 15,000 times per
second by the controller circuitry, while the ratio of the on/off times is varied in response to the input demanded by the throttle. An array of filter capacitors connected directly across the battery provides the instantaneous current required by the power switching circuitry and in this way provides battery ripple current filtering and voltage spike suppression. The plug diode provides a path for armature current to flow during plug braking.

Figure 24 Motor Controller Block Diagram
The motor controller is basically a step-down (buck) converter. The following figure is a simple schematic of a buck converter to show the basics of how it works [30]. The L and C form a low pass filter.

![Figure 25 Step-Down (Buck) Converter](image)

The sawtooth control signal is compared to a control voltage. The time when the signal is below the control voltage is $t_{on}$, otherwise it is $t_{off}$, and the period of the signal is $T_s$. The duty cycle $D$ is defined as follows:

$$ D = \frac{t_{on}}{T_s} = \frac{\dot{V}_{control}}{V_x} $$  \hspace{1cm} (8)

The output voltage is calculated in terms of the switch duty ratio.

$$ V_o = \frac{1}{T_x} \int_0^{T_x} v_o(t)dt = \frac{1}{T_x} \left( \int_0^{t_{on}} V_d dt + \int_{t_{on}}^{T_x} 0 dt \right) = \frac{t_{on}}{T_x} V_d = D V_d $$  \hspace{1cm} (9)

When the switch is on, the diode in the previous figure becomes reverse biased and the input provides energy to the load as well as the inductor. When the switch is off, the inductor current flows through the diode, transferring some of its stored energy to the

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load. In continuous conduction mode, there is always a positive current supplied to the load. The following formula shows that $V_o$ will always be equal to or less than $V_d$ since $D$ is never greater than 1.

$$\frac{V_o}{V_d} = D$$  \hspace{1cm} (10)

The following graph shows data taken from the electric vehicle before the hybrid conversion. The resistance of the load (i.e. the motor and motor controller) was calculated at each data point using Ohm’s law and varies from 0.035 ohms at 178 amps to 31 ohms at 2 amps.

![Figure 26 Driving Cycle Sample](image-url)
The following figure illustrates a typical driving cycle power demand, which can go as high as 11 kW. This is the power demanded by the 11.5 hp series excited DC motor through the solid-state motor speed controller.

Figure 27 Power Demand during Driving Cycle
CHAPTER 4

OPERATION MODE

Before the fuel cell was installed, data was collected to obtain a load profile of the vehicle (see Figure 25). The maximum power demand of the vehicle (about 11kW) determines whether the fuel cell or the battery bank should be the peaking unit of the system. The base unit provides up to a certain amount of power, and a peaking unit provides the excess power in times that demand exceeds the base power.

Case 1: Fuel Cell as Peaking Unit

The following graphs will illustrate the operation cases. Case 1 is when the fuel cell serves as the peaking unit. Notice that the fuel cell output voltage is constant because the DC-DC converter works to keep it so, but that the battery voltage droops when there is a high load current. At times of low load, the battery bank supplies the current. The fuel cell output voltage is so low that the battery bears the entire load current. But when the load current increases enough for the battery voltage to drop below the set fuel cell voltage, the fuel cell supplies the rest of the power.
Figure 28 Voltage and Current Response in Case 1

Figure 29 Fuel Cell as Peaking Unit
Case 2: Battery Bank Fuel Cell as Peaking Unit with Set Peaking Level

In Case 2, the battery bank is the peaking unit. The fuel cell DC-DC converter voltage is set higher. This means that the fuel cell will provide all the current because the battery does not see enough voltage drop across its internal resistance to provide any current. The fuel cell will continue to provide current to match the demand until the fuel cell is providing 5.5kW of power. At this point, the DC-DC converter acts to protect the fuel cell from a large power demand by decreasing its output voltage. This decrease in output voltage allows the battery bank to provide more current to the load, as can be shown using formula (1) from Chapter 3. $V_S$ and $R_B$ are constant, being properties of the batteries. Therefore $I$ (the current coming out of the battery) cannot increase unless $V$ (in this case, the output voltage of the DC-DC converter) decreases. Since $V$ is decreasing to avoid overtaxing the fuel cell, the battery bank can supply more current.
Figure 30 Voltage and Current Response in Case 2

Figure 31 Battery Bank as Peaking Unit
By manipulating the output voltage of the DC-DC converter, we can control at what points the battery bank or the fuel cells supply the current.

By using case 2, the lifespan of the battery bank is increased because the batteries will rarely see excessive discharge. For example, a battery that can be charged through 10,000 cycles when discharged 5% each cycle can only be charged through 1,000 cycles when discharged 50% each cycle.

When diodes and current shunts are in the system, the voltage drop across the diodes will droop slightly depending on the current draw. If the output of the DC-DC converter droops, as a result of the combination of the reality of the converter and the added diodes and shunts, then at high current loads the fuel cell voltage will drop a little more allowing the batteries to provide more current.

When a closed sensor feedback loop is introduced, such as already exists in the DC-DC converter, then the voltage output of the DC-DC converter can be greatly reduced in times of high load current to protect the fuel cell from a power demand over 5.5kW and allow the batteries to furnish these current spikes. Another method of control is already being used by the DC-DC converter, where the output voltage is reduced gradually, beginning at the current where the maximum power draw from the fuel cell is realized.
Case 3: Battery Bank Fuel Cell as Peaking Unit with Changing Peaking Level

During startup time, the fuel cell cannot reliably provide 5.5kW. It can only be depended on to provide 2.5kW. The peaking level needs to be lower during warmup, and then raised during power on demand. The following graph shows how this control scheme works. Startup time is during the first hundred seconds.

Figure 32 Battery Bank as Peaking Unit with more Peaking during Startup
The peaking level is controlled by adding a resistance in the DC-DC converter control circuit. By not introducing any resistance, the peaking level is 5.5kW. By introducing a 650 ohm resistor, the peaking level is 2.4kW. A signal wire from the fuel cell indicates whether the fuel cell is in warmup (6V) or power on demand (9V) mode. The control circuit simply needs to add a 650 ohm resistance when the state signal wire is 6V, and remove it when the state signal is 9V. This can be done with a comparator circuit. A solid state relay must be used because the common in the DC-DC converter control circuitry is isolated from the vehicle system ground.

![Figure 33 Control Circuit to Change Peaking Level based on Fuel Cell State](image)

Figure 33 Control Circuit to Change Peaking Level based on Fuel Cell State
CHAPTER 5

SIMULATED AND EXPERIMENTAL RESULTS

This chapter will present some simulation results and experimental results collected during tests. The simulation results were used to determine the test setups for collecting the experimental data. Data was collected with and without the battery bank attached.

Simulated Results

The following figure is a simplified schematic of the fuel cell vehicle. This first simulation will consider if the fuel cell voltage is higher than the battery voltage. The 75 Vdc source represents the DC-DC converter output. The 73.3Vdc source represents the internal battery voltage and the resistance tied to it represents the internal battery resistance.

![Figure 34 Simple Vehicle Simulation with Large Fuel Cell Voltage](image)

Figure 34 Simple Vehicle Simulation with Large Fuel Cell Voltage
R3 represents the load resistance. As the load resistance increases, the current draw into the load drops. The following figure shows that with the higher fuel cell voltage, most of the current into the load is drawn from the fuel cell. During low loads, when the load resistance is high, the battery does not see enough voltage drop across its internal resistance to supply any current. Having the diode in the circuit causes the voltage to droop more and allow the battery bank to provide more current. However, this passive power control does not allow enough droop to be used alone. Even during high load, the battery does not supply enough current to protect the fuel cell from loads exceeding 5.5kW.

Figure 35 Current Drawn from Battery and Fuel Cell vs. Load Resistance with Large Fuel Cell Voltage
If the fuel cell voltage is dropped to 65V, the battery bank supplies most of the current demand. More current is provided when the resistance of the load is small than when it is large.

![Diagram of a simple vehicle simulation with low fuel cell voltage](image)

Figure 36 Simple Vehicle Simulation with Low Fuel Cell Voltage

![Graph showing current draw from battery and fuel cell vs. load resistance with small fuel cell voltage](image)

Figure 37 Current Drawn from Battery and Fuel Cell vs. Load Resistance with Small Fuel Cell Voltage
The motor controller circuitry was also simulated to demonstrate how it uses switching the maintain voltage to the motor. The following figure shows a basic step down pulse width modulated DC-DC converter. Figure 24 shows this setup with more detail. R1 is the armature of the motor, and L1 is the field winding of the motor. D1 is the freewheeling diode and D2 is the plug diode, as discussed in Chapter 3. By altering the square wave signal (V3), the current provided to the load changes. This square wave is representative of the control signal generated in the motor controller, and is based on the gear the vehicle is in and how far the acceleration pedal is depressed. In the shown example, the current to the motor reaches about 28 amps and hold steady.

Figure 38 P-Spice of Motor Controller and Motor
While there are ways to model the fuel cell itself [18] as discussed in Chapter 2, from the vehicle perspective it is just as accurate to simulate the fuel cell as a constant voltage source since the fuel cell has a regulated 48V output.

The simulations can be combined to show a larger system schematic.
Experimental Results

To get experimental data, the motor controller and the motor were replaced with a variable load bank. Further vehicle integration is being done so that the vehicle itself will be connected. However, using a load bank makes it easier than driving the vehicle to collect data from a long period of high load conditions. The first test was a simple configuration without a battery bank, as shown below.
When the current demand rises to demand more than 5.5kW from the fuel cell, the DC-DC converter drops the voltage to protect the fuel cell from seeing a high load which would shut it down.
A closer look at the time that the DC-DC converter voltage begins to drop shows that this happens at approximately 70 amps of load current.
Drooping and inherent losses cause the difference between the DC-DC converter output voltage and the load voltage. The drop in voltages seen in the previous and following figures occur during a time of high current load in normal operation when the DC-DC converter drops its output voltage to protect the fuel cell from high power demand. When the DC-DC converter output drops, it is because the fuel cell is already supplying 5.5kW and cannot supply any more. If the batteries were added, as is seen in test case 2, the batteries would supply more current instead of allowing the voltage to drop.
The next figure shows the voltage drop across the diode, which is not constant, but relies on the load current. The diode was put into the system as an attempt to control the peaking point in the circuit, before it was realized that the DC-DC converter already adjusts its output voltage to protect the fuel cell. The small variance in voltage shows it is unlikely that this drop at high currents would allow the battery to supply sufficient current to protect the fuel cell without the active control in the DC-DC converter.
Because the DC-DC converter protects the fuel cell from high loads, the 48V input to the converter never changes regardless of the current drawn by the load.
The following graph clearly shows the knee around 72 amps at which load current demand causes the DC-DC converter to reduce its output voltage so that the fuel cell is not overburdened.
Other testing was done using both the battery bank and the fuel cell to show how they would share the power load. The following figure shows the test setup used.

Figure 47 DC-DC Converter Output vs. Load Current

Figure 48 Test Case 2 Setup
The DC-DC converter can be adjusted to provide different voltages as its output. The next graph shows two different trends. In the first trend, which is the lower line, the output voltage of the DC-DC converter is set to 72V. In the second trend, the output voltage is set to 75V. The following graph shows both trends at once, relating output voltage to load current. In trend 1, the output voltage does not drop until the load current is approximately 100 amps, but in trend 2 the output voltage begins to drop around 50 amps. This is because the 5.5kW limit of the fuel cell occurs at less current at higher voltages. However, the two trends meet at 100 amps.

Figure 49 Load Current vs. Output Voltage of DC-DC Converter with Two Distinct Trends
As predicted in Chapter 5, the fuel cell can be used as a peaking unit. The battery supplies current up to a certain amount until it is limited by the output voltage of the DC-DC converter. The fuel cell supplies any excess current until the DC-DC converter begins to lower its output voltage when the power demand on the fuel cell reaches 5.5kW.

The same thing happens in the second trend except the load currents at which the regions start and end are shifted towards lower current demands. The DC-DC converter output voltage is now so high that the batteries do not supply the low current demands. The point at which the output voltage of the DC-DC converter drops occurs at a lower load current.
Figure 51 Current Division in the Second Trend (Vf=75V)
SUGGESTIONS FOR FURTHER STUDY

Work on this project will remain ongoing. During the writing of this thesis, there was not time to introduce a battery charging path. There are plans to do this and to also look into regenerative braking so that some energy can be recaptured into the system during braking to improve efficiency. Also, the battery bank could be replaced by supercapacitors. The ability of the supercapacitors to store short bursts of power makes the vehicle better able to use regenerative braking.

A control circuit is being developed which will monitor whether the fuel cell is in warmup mode or normal operation, and adjust the output voltage of the DC-DC converter to protect the fuel cell from high loads during startup. After this change, the vehicle will be ready to be actually powered by the scheme described in this thesis.

This thesis shows how either the fuel cell or the battery bank can be the peaking unit, and how the level of peaking can be adjusted. Studying what options will optimize performance would be interesting as well.

It may be interesting to compare vehicle performance with different battery capacities to find an optimum capacitance and weight.
CHAPTER 7

CONCLUSIONS

The hybrid fuel cell and battery bank vehicle can be adjusted so that either the fuel cell or the battery bank is the peaking unit. The load current demand at which the peaking begins can also be adjusted. It is better to have the battery bank be the peaking unit so that it is easier to protect the fuel cell from high power demands, since the 5.5kW fuel cell used is unable to provide enough power to run the vehicle alone in all situations.

The diodes installed into the vehicle were an attempt to control the peaking levels of the system before it was realized that the DC-DC converter had already been adjusted to protect the fuel cell. They are unnecessary and only cause power loss and heat.

The hybrid vehicle design shown has been tested at high current demands and is ready to power the vehicle.
REFERENCES


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