DESIGN OF A CONTROL STRATEGY FOR A FUEL CELL / BATTERY HYBRID POWER SUPPLY

A Thesis

by

RICHARD CHARLES SMITH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Electrical Engineering

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Approved by:

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ABSTRACT

Design of a Control Strategy for a Fuel Cell/Battery Hybrid Power Supply.
(August 2009)
Richard Charles Smith, B.S., The University of Texas at Austin
Chair of Advisory Committee: Dr. Mehrdad Ehsani

The purpose of this thesis is to design hardware and a control strategy for a fuel cell/battery hybrid power supply. Modern fuel cell/battery hybrid power supplies can have 2 DC/DC converters: one converter for the battery and one for the fuel cell. The hardware for the power supply proposed in this thesis consists of a single DC/DC buck converter at the output terminals of the fuel cell. The battery does not have a DC/DC converter, and it is therefore passive in the system. The use of one single converter is attractive, because it reduces the cost of this power supply. This thesis proposes a method of controlling the fuel cell's DC/DC buck converter to act as a current source instead of a voltage source. This thesis will explain why using the fuel cell's buck converter to act as a current source is most appropriate. The proposed design techniques for the buck converter are also based on stiff systems theory.

Combining a fuel cell and a battery in one power supply allows exploitation of the advantages of both devices and undermines their disadvantages. The fuel cell has a slow dynamic response time, and the battery has a fast dynamic response time to fluctuations in a load. A fuel cell has high energy density, and a battery has high power density. And the performance of the hybrid power supply exploits these advantages of the fuel cell and the battery. The controller designed in this thesis allows the fuel cell to operate in its most efficient region: even under dynamic load conditions. The passive battery inherits all load dynamic behavior, and it is therefore used for peaking power delivery, while the fuel cell delivers base or average power.

Simulations will be provided using MATLAB/Simulink ® based models. And the results conclude that one can successfully control a hybrid fuel cell/battery power supply that decouples fluctuations in a load from the fuel cell with extremely limited hardware. The results also show that one can successfully control the fuel cell to operate in its most efficient region.

To my brother Rodney

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TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

FIGURE Page

LIST OF TABLES

CHAPTER I
INTRODUCTION

This chapter introduces the reader to the concept of hybrid power supplies and why they are important. Previous work on hybrid power supplies similar to the one in this thesis is presented. The problem that this thesis aims to solve is stated. A summary of this thesis is given at the end of this chapter.

1.1 Introduction to Power Supplies

The invention of power semiconductor devices such as diodes, metal-oxide-semiconductor-field-effect transistors (MOSFET), silicon-controlled rectifiers (SCR), gate-turn-off thyristors (GTO), and insulated-gate-bipolar transistors (IGBT), has allowed the advent of power electronic converters [1] [2]. With the use of power electronic converters, or more simply power electronics, one can design power supplies. What is a power supply? A power supply takes a single source of electric power such as a battery, fuel cell, solar cell, wall outlet, etc… and delivers that electric power at a regulated DC voltage. It is possible for a power supply to serve multiple loads, and it is also possible for a power supply to deliver power at multiple DC voltage levels. But for the purposes of this thesis, only the single load single voltage case will be discussed.

Since power supplies can utilize a variety of sources, their sources' naturally occurring properties also need to be mentioned. Some properties are attractive for specific applications, and others are not. Specific power is the maximum available power that a source can deliver per unit weight (W/kg). Power density is the maximum available power that a source can deliver per unit volume (W/L). Specific energy is a source's energy

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This thesis follows the style and format of the *IEEE Transactions on Energy Conversion*.

storage capacity per unit weight (Wh/kg). Energy density is a source's energy storage capacity per unit volume (Wh/L). Another property is the source's dynamic response time in changes in power output. The aforementioned properties come from [3] and [4], and they will be used throughout this thesis.

What is a hybrid power supply? A hybrid power supply combines 2 or more sources that work together to deliver or store power to act as a single power delivery unit. But the purpose of a power supply (hybrid or not) is mainly to deliver power at a regulated DC voltage level.

The main components of a hybrid power supply consist of at least two devices that deliver or store power, at least one power electronic converter, and the controller that regulates the converter's DC voltage. Figure 1.1 gives an example of a hybrid power supply with two sources, one converter for each source, and one load. Source number 2 is a storage element, because power can flow in when the load's power demand is low, and power can flow out when the load's power demand is high.

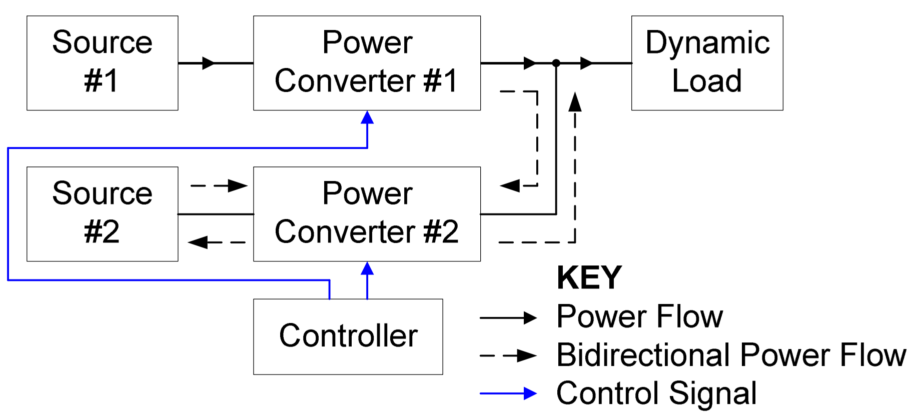

Figure 1.1: General concept of a hybrid power supply

Why use hybrid power supplies? One advantage that hybrid power supplies have over regular power supplies is that hybrid power supplies can store excess energy in one of its sources: such as a battery or ultracapacitor. Since hybrid power supplies utilize two sources, they can couple one source that has high specific power and one source that has high specific energy, and the hybrid power supply's performance displays high specific energy and high specific power. Hybrid power supplies can also couple one source that has a slow dynamic response time and one that has a fast dynamic response time in their power output, and the hybrid power supply displays a fast dynamic response time. A designer can choose which sources to use in a hybrid power supply based on their inherent properties, and the designer can design the hybrid power supply to exploit specific properties between its sources.

In a general sense, a hybrid power supply can be designed to exploit the advantages of each of its sources, and it can simultaneously undermine its sources' disadvantages [3] [4].

1.2 Uses of Fuel Cells and Batteries

A fuel cell is an electro-chemical device that converts chemical energy into electrical energy and heat as a by product. The fuel cell will continuously deliver electric power as long as fuel is supplied. The most commonly used fuels are hydrogen and oxygen. Just like the fuel cell, a battery is an electro-chemical device that converts chemical energy into electrical energy. But a battery does not have chemical fuel continuously injected to supply its electrical power output. A battery can only store and release energy; it cannot be refueled like a fuel cell. Thus a battery is a storage device; whereas a fuel cell is a generating device. In fact, batteries and fuel cells have very similar properties, since they are both electro-chemical devices.

Because of their greater efficiency, fuel cells are becoming attractive as stationary backup power supplies for commercial buildings [3] [5]. A conventional backup power generator consists of an internal combustion engines (ICE) and an electric machine. For a conventional generator to produce electricity, fuel is first supplied to the ICE to produce mechanical energy. Then the mechanical energy in the ICE turns the electric machine to deliver electricity. Since fuel cells convert chemical energy directly into electricity, they bypass the intermediate step of the ICE: which is to convert fuel into mechanical energy. Thus fuel cells can be more efficient than conventional generators. Fuel cells also offer higher partial load performance than that of ICEs. An ICE can operate at a maximum fuel efficiency of 34%; a fuel cell can operate at efficiencies as high as 50% [3]. Fuel cells are currently available for backup power supplies with ratings as high as 250kW [5] [6]. Since fuel cells generate so much excess heat in addition to electricity, this excess heat can be utilized for heating a building [6] [7].

Fuel cells have no moving parts, so that also means they make no noise. And fuel cells also have less maintenance than that of ICEs. It is incredibly inefficient to start-up and shutdown the fuel cell as a result of changes in the load, because fuel cells take a long time to warm up. So in a hybrid power supply, the fuel cell does not have to shut down when the load drops to low power demands. The battery can store extra power from the fuel cell during low load conditions, and as a result, the fuel cell does not have to shut down. And the power output of the fuel cell does not have to follow changes in the load. This cooperative operation of a fuel cell and battery can optimize the efficiency of the fuel cell.

A fuel cell's voltage is a function of the current, so a power supply with a fuel cell must include a DC/DC converter, because the fuel cell cannot deliver a constant DC voltage at various power levels. Fuel cells coupled with an energy buffer gives a dynamic response time of milliseconds. Fuel cells have a dynamic response time of several seconds to a few minutes. A fuel cell's power output depends on the supply of fuel, and the fuel supply cannot change on the order of milliseconds. The fuel pumps must take time to increase or decrease the supply of fuel. Since the fuel supply takes several seconds to increase or decrease, the fuel cell's power also takes several seconds to increase or decrease. An energy buffer such as a battery can also be used to compensate for the slow warm up time for a fuel cell.

As with a system that posses advantages, there are always disadvantages. One obvious disadvantage of fuel cells is their initial cost, but since fuel cells are not mass produced and readily available on the market, their cost could go down in time. Pure hydrogen is also not readily available. A summary of fuel cells' and batteries' advantages and disadvantages is listed below.

Advantages of fuel cells

- Will generate power as long as fuel is supplied
- High specific energy compared to a batteries
- Zero emissions
- Silence
- No moving part

Disadvantages of fuel cells

- Dynamic response time of several seconds to a few minutes
- Must take time to warm up before full power output can be obtained
- Cannot deliver full power at cold start
- Voltage varies widely with current
- hydrogen is not a readily available fuel
- High initial cost

Advantages of batteries

- Dynamic response time on the order of milliseconds
- Can charge and discharge for up to 1000s of cycles

Disadvantages of batteries

- Long recharge time
- Low specific energy compared to a fuel cell
- Limited discharge time

More details about the behavior of fuel cells and batteries are given in Chapter II.

1.3 Problem Definition

The problem that this thesis aims to solve is to successfully design a control strategy for a fuel cell / battery hybrid power supply with a single DC/DC buck converter. Figure 1.2 shows a block diagram of the exact power supply that is designed in this thesis. This power supply should deliver any level of power up to a certain rating, and the load voltage must operate at a nominal DC voltage level with 5% tolerance. We also want the battery's state of charge (SOC) to fall within a window. We want the battery to always readily accept charge incase the load power drops suddenly. And we want the battery to always have some available stored energy ready to deliver incase the load power suddenly increases. Fuel cells have an operating region where the efficiency is maximum, and we also want the fuel cell to operate in this region as often as possible. We can relax this fuel cell constraint temporarily to service the battery if the battery's current reaches unsafe levels or if its SOC gets too low. Complete details about the control we aim to achieve will be discussed in Chapter IV.

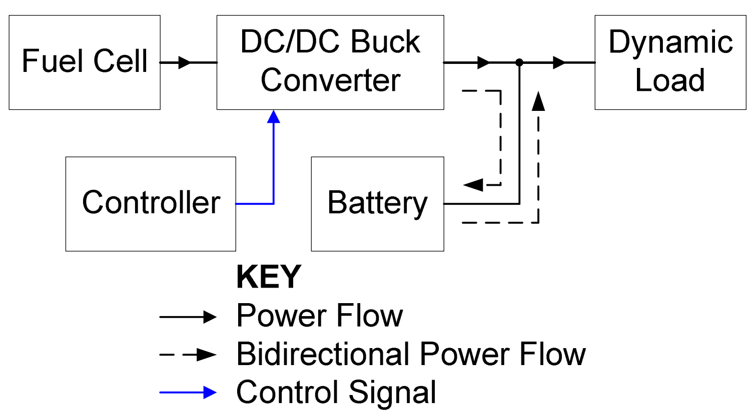

Figure 1.2: Block diagram of the power supply proposed in this thesis

As mentioned in the previous section, fuel cells have a high energy density, and their power output has a slow dynamic response time. Batteries have a high specific power, and their power output has a fast dynamic response time. So the proposed fuel cell / battery hybrid power supply can achieve high specific power, high specific energy, and its performance will display a fast dynamic response time.

1.4 Previous Work

The concept of using one converter to hybridize a fuel cell and a battery is not unique to this thesis. The textbook [4] also mentions this concept. In reference [4], the author proposes using the DC/DC converter and the fuel cell to charge the battery while also supplying the load when the load power is low. But when the load power is high, the battery will deliver full power to the load, and the fuel cell is turned off. Therefore only one device is delivering power at any point in time. The objective in this thesis is to have both the battery and the fuel cell deliver power simultaneously.

Similar work using the same hardware used in this thesis has been done by Z. Jiang, L. Gao, and R. A. Dougal [8]. What they did differently was that they did not use the buck converter's inductor current to track a reference that can also change during real-time. These authors measured the fuel cell current directly. It will be explained in Chapter III why controlling the buck converter's inductor current to track a reference is more appropriate than controlling the fuel cell current directly.

The work done by Alireza Khaligh, Amir M. Rahimi, Young-Joo Lee, Jian Cao, Ali Emadi, Stanley D. Andrews, Charles Robinson, and Caine Finnerty [9] also uses the buck converter to cause the fuel cell current to track a reference. But just like the authors in [8], these authors also do not measure or control the inductor current in the buck converter. The authors' work also includes a flowchart control algorithm similar to the flowchart proposed in Chapter IV of this thesis. But their flowchart determines the operating point for the fuel cell to ensure that the battery and the load voltage are operating within safety limits. The flowchart proposed in Chapter IV of this thesis accomplishes the task of ensuring that the battery and load voltage are within safety limits in addition to optimizing the fuel cell's power such that the fuel cell operates near maximum efficiency as often as possible.

The work done by N. Bizon, M. Raducu, and M. Oproescu [10] uses a bi-directional buck for the purposes of current ripple reduction in the fuel cell. They do control the current in the buck converter's inductor using bang-bang control, but they do not use their fuel cell and buck converter in a hybrid power supply with a battery. Current ripple reduction in the fuel cell is beyond the scope of this thesis, but this work is of interest, because the authors use the buck as a current source, similar to the use of the buck as a current source in this thesis. But this thesis uses fuzzy logic to control the inductor current in the buck converter.

This thesis also presents a new application of stiff systems theory to design the buck converter [11]. Stiff systems theory will be explained in Chapter III. This thesis also provides simulations over several seconds under various load conditions to test the robustness of the controller. The authors in references [8] and [9] only provided simulations over a few milliseconds.

1.5 Summary

Chapter I gave an introduction to the thesis and defined the problem which is solved. Chapter II gives background information on fuel cell and battery principles of operation. Chapter II will also present circuit equivalent models for the fuel cell and battery used in the simulations in this thesis. Chapter III introduces the reader to the buck converter and explains why the converter's operation as a current source is most appropriate. Chapter III also explains stiff systems theory to design the buck converter. Chapter IV introduces fuzzy logic and explains how it is used to control the buck converter's current. The high level control scheme with the objective of operating the fuel cell at maximum efficiency is also discussed in Chapter IV. Chapter V presents the Simulink model files used in this thesis. Some Simulink blocks have embedded MATLAB code, and their code is presented in the appendices. Chapter VI presents and explains the results of the simulations. Chapter VII finally gives some concluding remarks and prospects for future research.

CHAPTER II
FUEL CELL AND BATTERY PRINCIPLES

In this chapter the operational characteristics for typical fuel cells and batteries are discussed. High-level fuel cell and battery concepts are given the most attention. Circuit equivalent models for a fuel cell and battery are presented for use in the simulations in this thesis.

2.1 Fuel Cell Characteristics

A fuel cell is very similar to a battery in the sense that it delivers electric power directly from chemical energy. But a fuel cell will deliver power as long as fuel is supplied, whereas a battery will only deliver power until charge is depleted. There are many types of fuel cells available today: such as proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells, phosphoric acid fuel cells, solid oxide fuel cells, and molten carbonate fuel cells. To investigate all of these fuel cell types is beyond the scope of this thesis. We will use a proton exchange membrane fuel cell (PEMFC) - also called a polymer electrolyte membrane fuel cell - that is directly fed pure hydrogen and oxygen as its fuels [6] [7] [12]. Figure 2.1 shows the simplest concept of a fuel cell.

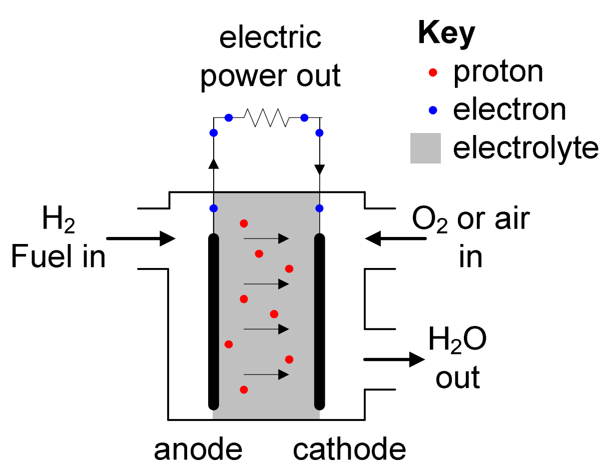

Figure 2.1: Simple hydrogen oxygen fuel cell

When the hydrogen is injected at the anode and enters the electrolyte, it ionizes. The electrons are freed from the hydrogen atoms, and the protons move across the electrolyte to the cathode to rejoin with oxygen and the electrons. The electrons cannot move through the electrolyte; therefore they must travel through the circuit to recombine with oxygen at the cathode. The name "proton exchange membrane" comes from the fact that only protons travel through the electrolyte. The overall chemical reaction that takes place within the fuel cell is

$$2H_2 + O_2 \rightarrow 2H_2O \tag{2-1}$$

But the overall reaction can be broken into two parts: the separate reactions that occur at the anode and cathode respectively. The hydrogen ionization reaction that occurs at the anode is

$$H_2 \rightarrow 2H^+ + 2e^- \tag{2-2}$$

The reaction at the cathode where oxygen recombines to form water is

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{2-3}$$

A single fuel cell (as in Figure 2.1) is only capable of delivering about 1V. To get a useful voltage, many cells must be placed in series to build a fuel cell stack. Figure 2.2 shows how to connect four fuel cells in series to produce a higher voltage. The stack voltage can easily be increased by adding more individual fuel cells. Obtaining a stack voltage as high as 200V is not unreasonable. Since a single fuel cell is not useful, the words "fuel cell," usually imply a fuel cell stack.

PEM fuel cells' start-up time to reach maximum power at room temperature is 2 minutes [12]. But the most efficient power level of a fuel cell is about 33% of the maximum power:

as indicated in Figure 2.3 and Figure 2.4. So it only takes about 30 seconds to reach power at maximum efficiency. Figure 2.3 gives the current-voltage behavior and power density of a typical PEMFC. You can see that voltage is not constant for various levels of current.

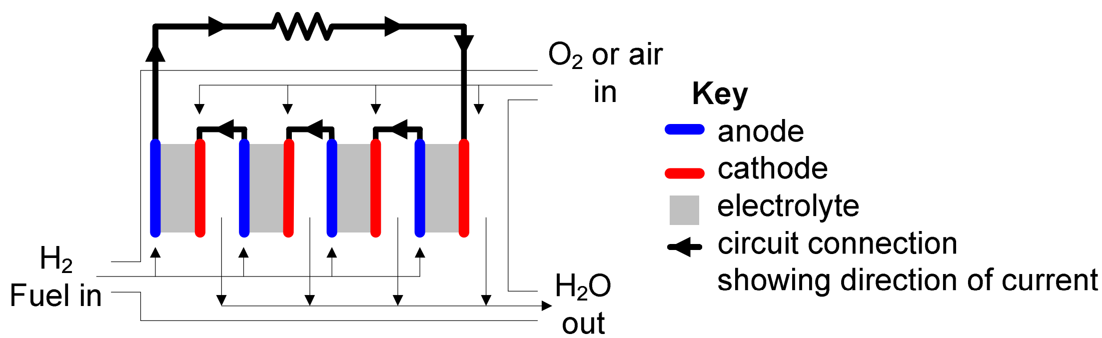

Figure 2.2: Fuel cell stack

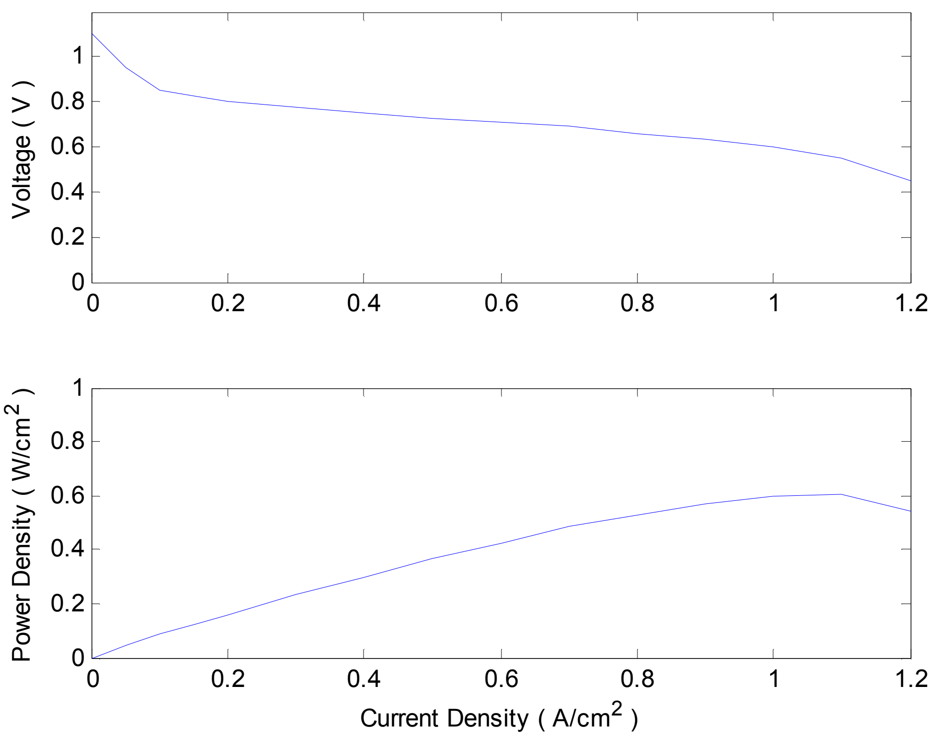

Figure 2.3: Typical fuel cell I-V and power curves (adapted from [3])

The warm up time for a fuel cell is slow, but even after they war up, fuel cells also have a slow dynamic response time. It is possible for a fuel cell's current to change instantaneously, but the average change in power delivery over time must be on the order of about 30 seconds [11]. The reason why the change in average power must be slow is due to the fact that the fuel cell is fed a gaseous or liquid fuel. It takes time for the air pumps and fuel pumps to inject more or less fuel into the fuel cell, and that in effect creates a slow dynamic response time. And obviously, the fuel cell can only deliver power as fuel is supplied.

A fuel cell delivers electric power directly from chemical energy just like a battery. But a fuel cell will deliver power as long as fuel is supplied, and a battery will only deliver power until charge run out. About 10% of the fuel cell's maximum power is devoted to ancillary devices: such as cooling fans, air pump, and waste water management. The ancillary devices that use the most amount of power are the fuel and air pumps.

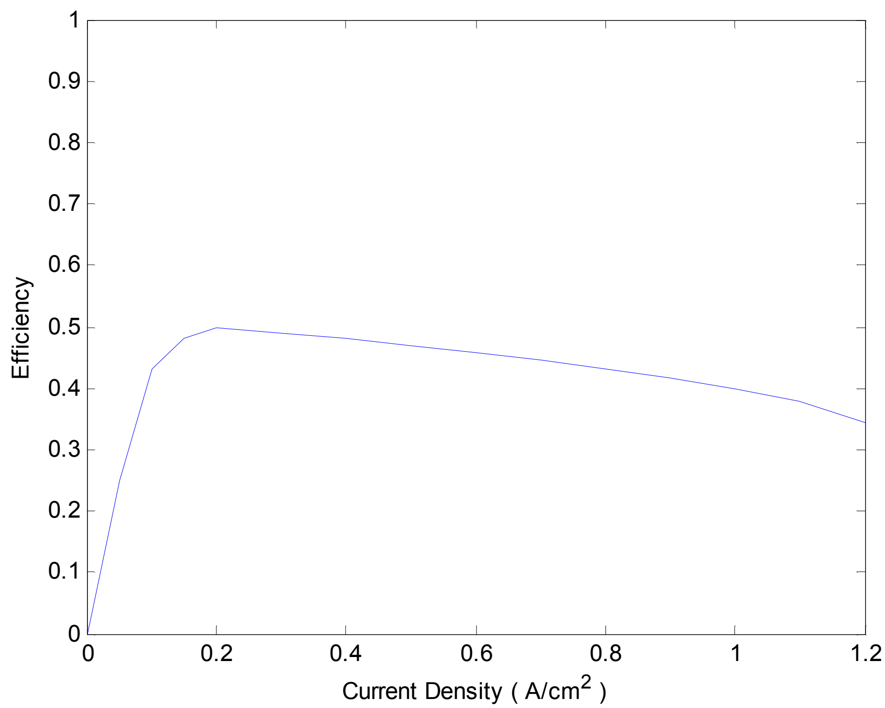

Figure 2.4: Fuel cell efficiency (adapted from [3])

The drop in voltage as current increases (shown in Figure 2.3) is due to inefficiencies in the reaction and a voltage drop in the electrodes. The electrodes are made of metal, so they have some resistance. We will model the various voltage drops of the PEMFC used in this thesis using equation (2-4). Figure 2.5 illustrates this equation.

$$V_{FC} = V_0 - V_{ACT} - V_{CON} - V_{OHM} \tag{2-4}$$

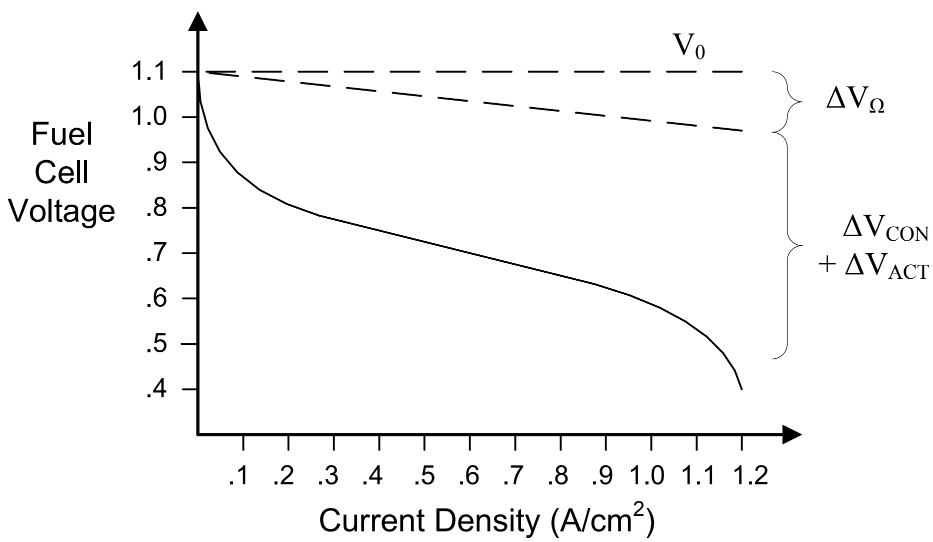

Figure 2.5: Causes of fuel cell voltage drop (adapted from [3])

V_0 is the fuel cell ideal voltage; V_{ACT} and V_{CON} are activation and concentration losses in the chemical reaction in the fuel cell; and V_{OHM} is the ohmic losses in the electrodes of the fuel cell. These three causes of voltage drop can be modeled as resistors in a fuel cell equivalent circuit shown in Figure 2.6.

In addition to a fuel cell's slow dynamic response time in average power, a fuel cell's voltage also has a slow dynamic response time. The fuel cell voltage is largely a function of the chemical reaction and partially a function of ohmic losses in the electrodes. But it takes tom for the reaction to reach equilibrium as a result in a current interrupt. So if the current were to be cut off, the voltage drop in ohmic losses would change immediately.

The voltage drop due to the activation and concentration losses will take several seconds to respond to changes in current. Figure 2.7 illustrates how a fuel cell voltage responds to a discontinuous current.

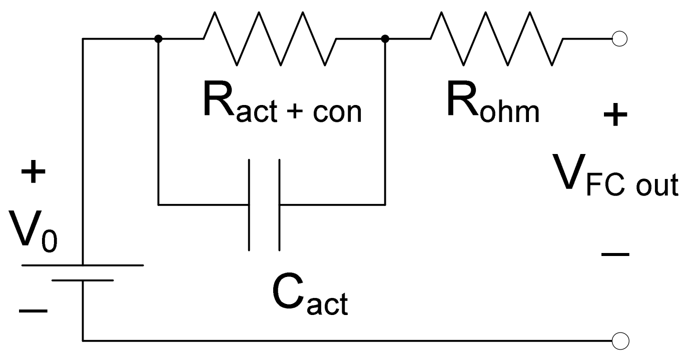

Figure 2.6: Fuel cell equivalent circuit

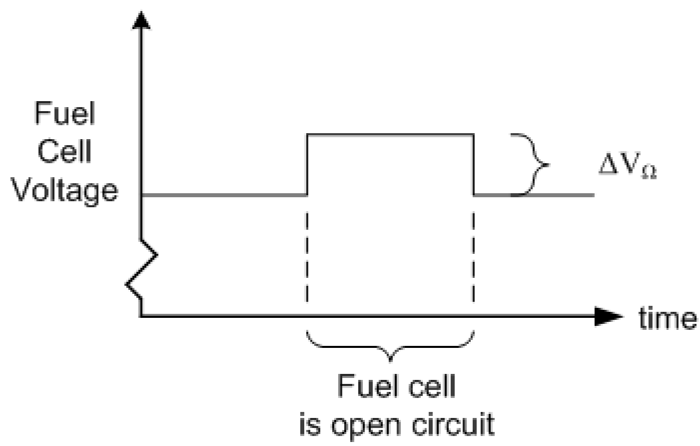

Figure 2.7: Fuel cell current interrupt

Figure 2.6 is a circuit equivalent model of a fuel cell that models the causes of voltage drop and a slow response time in the chemical reaction. A single resistor can model the combined activation and concentration losses. A separate resistor is needed to model the ohmic loses in the electrodes. Since the activation and concentration voltage drop have a response time of several seconds, the capacitor C_{ACT} models this time delay. So this circuit equivalent models the voltage behavior illustrated in Figure 2.7.

The fuel cell used in this thesis will deliver a discontinuous current, because the fuel cell's current is fed as the input current to the buck converter. And the buck converter has a discontinuous input current (to be explained in Chapter III). But its average power deliver over time will change slowly.

2.2 Battery Characteristics

Even though batteries and fuel cells have very similar characteristics because they are electrochemical devices, a battery is not a true power source like a fuel cell. A battery is a storage device, so that means that the net power of a battery over time is zero. The purpose of the battery in the hybrid power supply designed in this thesis is to store excess power from the fuel cell when the load demand is high, then release its stored energy when the load power is high. So the fuel cell will deliver continuous power and the battery is used to deliver peaking power. There are many types of batteries available on the market today: such as lead-acid batteries, nickel-Cadmium batteries, nickel-metal-hydride batteries, Lithium-ion batteries, etc… As with the different types of fuel cells, to explore each of these battery types is beyond the scope of this thesis.

To begin introducing properties of batteries, some key vocabulary definitions need to be discussed. Batteries store charge, but their charge capacity is not measured in coulombs; it is measured in Amp-hours (Ah). The relationship between Ah and coulombs is below.

$$\text{total storage capacity in coulombs} = Ah(3600) \tag{2-5}$$

The state of charge (SOC) of a battery is the amount of charge a battery has stored as a percentage of its total storage capacity. When the battery is fully charged, SOC = 100%. The depth of discharge (*DOD*) is the amount of charge the battery has discharged as a percentage of the total amount of discharge capacity. When the battery is fully discharged

DOD = 100% and *SOC* = 0%. The discharge capacity is the same in magnitude as the total storage capacity. The simple relationship between *SOC* and *DOD* is below.

$$DOD = 1 - SOC \tag{2-6}$$

Coulomb counting is one method to approximate a battery's *SOC*. Coulomb counting requires a digital computer such as a microcontroller to sample the battery current at a sampling period T_{CC}. The computer multiplies the most recent battery current sample at T_{CC} to get the change in coulombs between each sampling period. The change in coulombs is then divided by the total charge capacity of the battery to get a percent change in stored charge between sampling periods. Equations (2-7) and (2-8) show how coulomb counting can estimate a battery's *SOC* – where k is the sampling instant.

$$SOC[k] = SOC[k-1] + \frac{\Delta \text{charge}}{\text{total charge capacity}} \tag{2-7}$$

$$SOC[k] = SOC[k-1] + \frac{T_{CC} \sum_{k=0} I_{BATT}[k]}{(Ah\ rating)3600} \tag{2-8}$$

A battery behaves much like a voltage source, but it is not an ideal voltage source. Due to inefficiencies in the chemical reaction in the battery (just like a fuel cell), voltage does not remain constant for all values of current. As indicated in Figure 2.8, voltage degrades proportionally as current increases. A battery can be modeled as a simple voltage source in series with a resistor – shown in Figure 2.9 - to reflect the behavior in the I-V curve. The slope of the battery's I-V curve (and the value of R_B) depends on the type of battery used [13] [14].

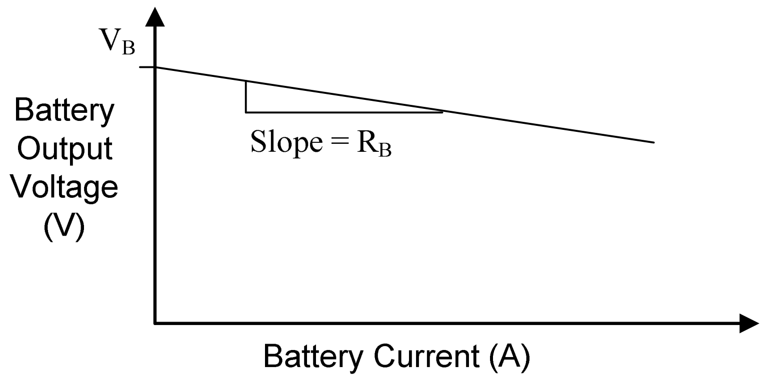

Figure 2.8: Battery I-V curve

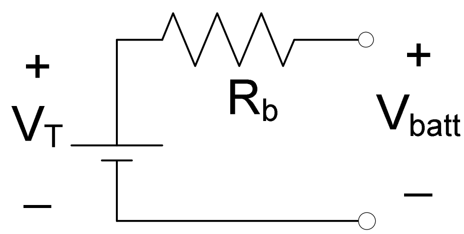

Figure 2.9: Battery equivalent circuit

The battery model used in this thesis is the circuit equivalent model above. Characteristics that reflect that of a nickel-metal hydride battery will be used for the battery model. NiMH batteries are attractive for power supplies and vehicles, because their voltage does not drop by much as current increases. That means that the value of R_B is small. They can also remain in operation over 1,000 charge-discharge cycles [13].

CHAPTER III
PROPOSED HYBRID POWER SUPPLY HARDWARE

In this chapter stiff system techniques used in this thesis for designing power electronics is presented. The buck converter operating principles are discussed. And the reason why it is important to use power electronics as a current source instead of a voltage source is also explained.

3.2 DC-to-DC Converter Principles

DC-to-DC converters are often used in regulated switch-mode dc power supplies. The buck converter is a switching power electronic device that converts a DC voltage input into a lower DC voltage output [1] [2]. Figure 3.1 shows a circuit diagram of the converter. The buck converter is typically used as a voltage source. But as will be explained later in this chapter, we will use the buck as a current source in this thesis. The buck converter is attractive as a current source, because it has an inductor at the output. Inductors are attractive as current sources, because they stabilize the current in them and reduce current ripple. The capacitor on the output voltage side is optional in this thesis. Typically in a buck converter, the output capacitor is used to stabilize the output voltage. But for the hardware presented in this thesis, the battery already achieves that task. The output capacitor is still useful as a noise filter for the battery current.

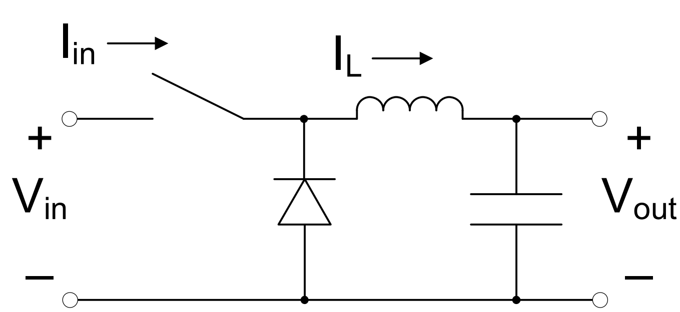

Figure 3.1: DC/DC buck (step-down) converter

Figure 3.2 shows the switching behavior of the buck converter. When the switch in Figure 3.1 is conducting, the diode is open circuit. When the switch is open circuit, the diode is conducting. Figure 3.3 explains the time intervals when the switch is conducting or not conducting (on or off). The duty cycle, D, is the percentage of the switching period of the buck when the switch is conducting. $(1 - D)$ is the percentage of the switching period when the switch is open (off). DT_{SWITCH} is the amount of time in milliseconds that the switch is conducting each switching period, and $(1 - D)T_{SWITCH}$ is the amount of time that the switch is open over each switching period.

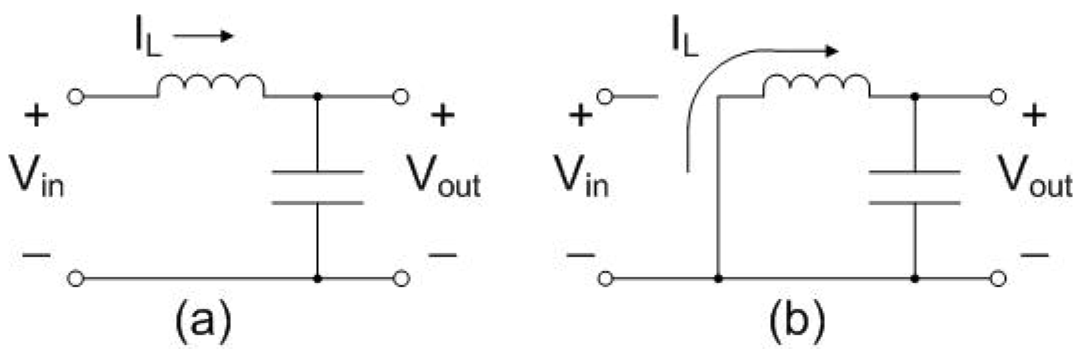

Figure 3.2: Buck converter with (a) switch closed and (b) switch open

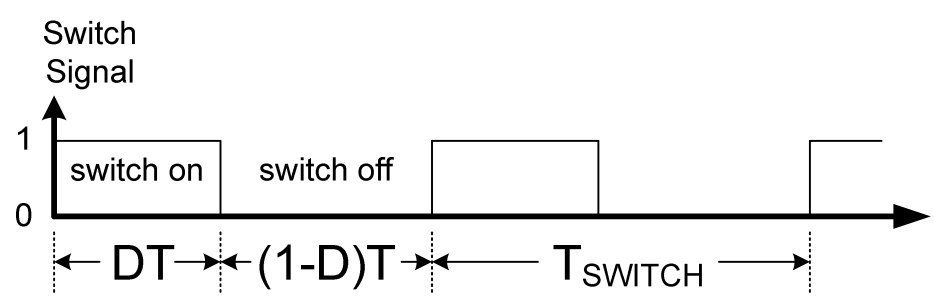

Figure 3.3: Switch on/off signal in the buck converter

So over every switching period we must have

$$D + (1 - D) = 100\% \qquad (3\text{-}1)$$

And the relationship between the input voltage and output voltage is

$$V_{OUT} = DV_{IN} \tag{3-2}$$

Power is conserved in the buck converter over each switching period; that is to say

$$P_{IN} = P_{OUT} = V_{IN} * I_{IN} = V_{OUT} * I_{OUT} = V_{OUT} * I_L \tag{3-3}$$

The average inductor current is the same as the average output current, because the average capacitor current is zero. So given equations (3-2) and (3-3), the relationship between input current and output current is

$$I_{IN} = DI_{OUT} \tag{3-4}$$

One thing very important about the buck converter is that the switch is in series with the input current. So the input current looks like the waveform in Figure 3.4.

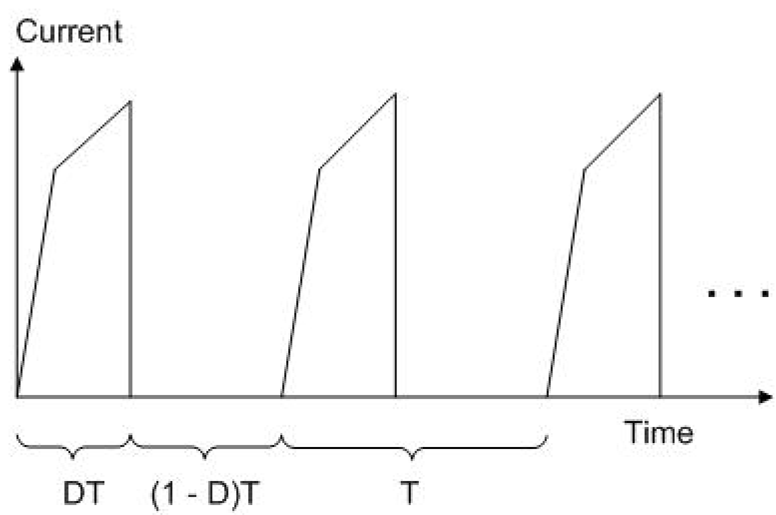

Figure 3.4: Input current waveform for the buck converter

It is impossible to have the input current to the buck converter track a reference; because, as shown in Figure 3.4, the input current is discontinuous. So it does not make sense to have the buck converter's input current track a reference. So it is most practical to have the inductor current track a reference. Also the inductor acts as a current stabilizer to reduce current ripple, so the inductor is a natural current source. As mentioned in Chapter I, this thesis improves upon the work done by the authors who wrote references [8] and [9], because those authors attempted to get the buck converter's input current to track a reference. But as shown in Figure 3.4, it is not appropriate to do that.

One can utilize a harmonic filter at the input of the buck converter to cause the input current to at least be continuous. But adding a filter increases hardware components and the objective in this thesis is to use as little hardware as possible. One would have to have a substantial number of filters to reduce the input current ripple enough to begin to control the input current to track a reference.

3.2 Using the Buck as a Current Source

In Figure 3.5 we show a hybrid power supply with the output of the converter in Figure 1.2 modeled as an ideal voltage source. In Figure 3.6 we show the output of the converter modeled as an ideal current source. The battery equivalent circuit is modeled as a simple voltage source in series with a resistor as shown in Chapter II.

Surprisingly, the circuits shown in Figures 3.5 and 3.6 operate very differently: as shall soon be shown. In this thesis we use the buck converter to operate as a current source - when the buck is traditionally used as a voltage source. Not only is the buck converter attractive to use as a current source because of the inductor on the output, but it is essential to use a converter as a current source in the overall hybrid power supply concept in Figure 1.2. The theorem on the next page will prove why it is most appropriate to use a current source as the output of the buck converter.

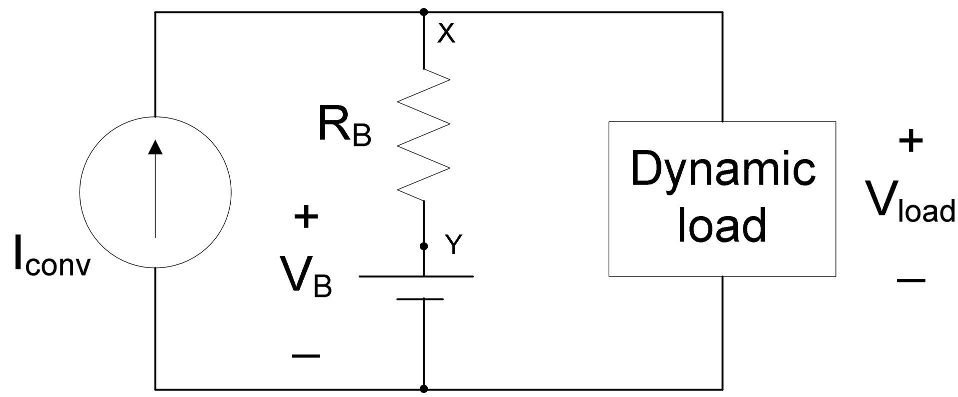

Figure 3.5: Hybrid power supply with a battery and an ideal current source

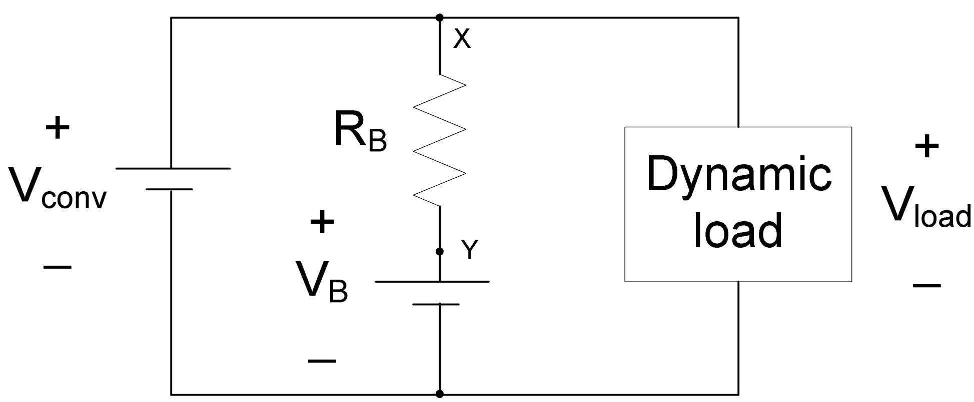

Figure 3.6: Hybrid power supply with a battery and an ideal voltage source

Theorem (3-1): If an ideal voltage source is connected in parallel with a battery to deliver power to a load, then it is impossible for both the voltage source and the battery to deliver power to the load simultaneously.

Proof: Assume that V_{conv} is an ideal voltage source as in Figure 3.6. We have three different scenarios to analyze.

- If $V_{conv} < V_B$ then the converter will not deliver power. Thus the fuel cell is practically removed from the system and the battery delivers all of the power to the load.

- If $V_{conv} > V_B$ then the battery will not deliver power. The battery will only receive charge. The converter will deliver the combined power to the load and the charging power to the battery.
- If $V_{conv} = V_B$ then the battery will not deliver power and will not receive charge. Current will not flow from point x to point y in the circuit, because current only flows from high voltage to low voltage. Since there is no voltage difference across R_B, the battery current is zero. The converter will deliver all power to the load, and the battery is practically idle.

Hence there is no scenario where the battery and converter simultaneously deliver power to the load. □

The theorem just demonstrates a classic example of the concept: you don't put two voltage sources in parallel. But putting a voltage source and a current source in parallel causes no problems. So if the converter for the fuel cell is used as a voltage source then it is impossible to employ a strategy for the fuel cell to deliver base load and use the battery for load peaking. No matter what control algorithm we use, one thing that always must remain true is the law of conservation of energy.

$$P_{load} = P_{batt} + P_{fuel\ cell\ converter} \tag{3-5}$$

Since we will operate the buck as a current source that means the load voltage, the converter output voltage, and the battery voltage are the same. The battery bears the task of maintaining a nearly constant load voltage in addition to delivering power when the load is peaking. Looking at Figure 3.1, the output voltage of the buck is also the battery voltage.

$$V_{BATT} = V_{OUT} = V_{LOAD} \tag{3-6}$$

Since V_{BATT} is relatively constant, one choose exactly how much power the converter is delivering by choosing the inductor current reference.

$$P_{CONVETER} = V_{BATT}*I_L \tag{3-7}$$

Controlling the power of the converter effectively controls the power of the fuel cell. Since the controller determines the power of the fuel cell under dynamic load conditions, the load dynamics are inherited by the battery. Anytime there is a sudden rise or fall in the load, the battery notices this behavior and responds; whereas the fuel cell does not endure any load dynamic behavior. Also if the power delivered by the converter is larger than the power of the load, then the battery power is negative. That effectively means the battery is charging. So the task of decoupling the load dynamics from the fuel cell are achieved by simply operating the buck converter as a current source. The fact that the battery acts as a stiff voltage source makes control of the power supply proposed in this thesis very easy, because we only have to control I_L.

Of course the fuel cell's power will not be constant, because the fuel cell's power is determined by the high-level controller. The high level controller chooses a reference value for I_L, and that effectively chooses the fuel cell power. But the controller does not have to keep the reference for I_L constant. As mentioned in the problem definition in Chapter I, we want the fuel cell to operate at its most efficient region as often as possible. But the controller can choose different values for I_L when necessary if the load is too high or too low and the battery's power is exceeding its maximum rating. More precise instructions on exactly how the controller operates is the topic of Chapter IV.

Using the buck converter as a current source can also provide the additional advantage of isolating the battery from the circuit entirely. For example, if the buck converter delivers the exact same amount of power as the load demands, then the battery delivers zero power. One can develop a control strategy to have the inductor current track the load current and the battery is used as little as possible. But the control strategy developed in Chapter IV does not try to achieve this objective. The objective in this thesis is to have the fuel cell operate in its most efficient region as often as possible. But the option of isolating the battery is still viable.

3.3 Inductor Design Using Stiff Systems Theory

Before we explain stiff systems theory, we first need to explain the concept of drift current and current ripple. As mentioned earlier in this Chapter, an inductor serves two purposes: to reduce current ripple and to stabilize the average current over several switching periods. Techniques can be applied to the buck converter to exactly calculate how much current ripple the designer is willing to tolerate in references [1] and [2]. But we are not going to design the inductor to calculate the maximum tolerable current ripple in the inductor. We want the average current in the inductor to "drift" only slightly over a few switching periods of the buck converter. We say the vague phrase "a few switching cycles," because exactly how many cycles to consider is left for the designer to decide. In this thesis we will use 10 cycles; we want the inductor's average current to be stable over 10 cycles, and we only want it to drift slightly over those 10 cycles. Figure 3.7 shows a current waveform along with its drift current.

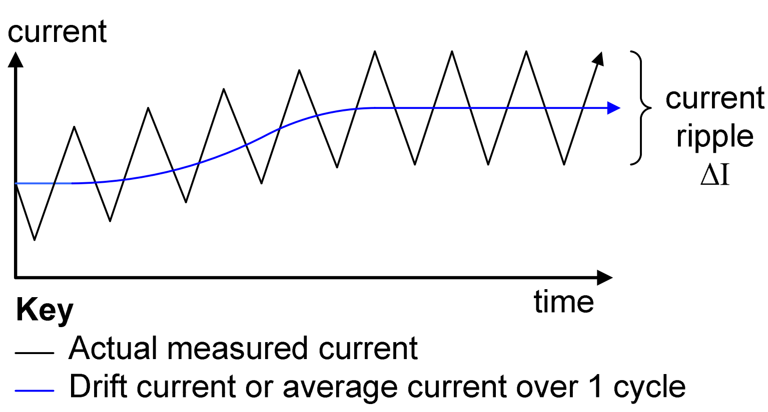

Figure 3.7: Drift current, measured current, and current ripple

The average current taken over 1 cycle is defined as

$$I_{AVE} = \int_{T_{SWITCH}}^{o} i(t)dt \qquad (3\text{-}8)$$

To distinguish between drift current and average current, drift current is the consecutive behavior of the average current over many cycles. It is this drift current behavior that we are most interested in, and the drift current's behavior is dependent on the time constant of the inductor. Drift current is what we want the inductor to stabilize.

Stiff systems theory is applied to systems with two or more time constants [11], and the buck converter has two time constants: the switching period of the switch, T_{SWITCH}, and the inductor time constant, τ_L. The converter needs to be able to respond faster than the inductor current. The converter time constant needs to be so fast compared to the inductor time constant, such that when the controller takes any action, the inductor's behavior barely responds to that action. That is to say he inductor time constant needs to be much greater (slower) than the switching period of the buck converter. The switching period of the buck converter is the smallest amount of time that the controller has to take any action, so the time constant of the controller is equal to the time constant of the buck.

If you have a system with time constant, T_S, under control and a controller with time constant, T_C, then stiff systems theory says that the controller's time constant must be at least ten times faster than the system's time constant to achieve proper control. Stiff system's theory can also be used to control unstable systems. When the unstable system is diverging out of its desired operating range, the controller's response is so fast compared to that of the system, the controller is able to make adjustments, such that the unstable system continues to operate satisfactorily within its desired operating range [11].

We will apply the stiff systems concept to design the buck converter. We can calculate the appropriate inductor size using its time constant. We want the drift current in the inductor to be stiff compared to the switching period of the converter. So we need the switching period of the converter, T_{SWITCH}, to be at least ten times faster than the inductor time constant, τ_L. Below is the stiff systems theory calculation used to calculate the inductor value used in the simulations of this thesis.

Table 3.1 lists the data used in this example, and this data is also used as parameters in the simulations. Since the load is assumed to be dynamic, we will use the average value for the resistive load, R_{AVE}.

Table 3.1

Given data for stiff systems calculation

$P_{load\ AVE} = 2$ kW	$V_{load\ AVE} = 70$ V	$R_{load\ AVE} = 2.45\ \Omega$
$f_{BUCK} = 10$ kHz	$T_{SWITCH} = .0001$ sec	

Stiff systems theory says that we must have

$$T_S > 10\ T_C \quad (3\text{-}9)$$

$$\tau L > 10\ T_{SWITCH} \quad (3\text{-}10)$$

$$\tau L > .001\ sec \quad (3\text{-}11)$$

Substitute the time constant, τ_L, for the equivalent L / R_{AVE}

$$L / R_{AVE} > .001\ sec \quad (3\text{-}12)$$

$$L / 2.45\Omega > .001\ sec \quad (3\text{-}13)$$

When we solve the inequality for L, we get the minimal value for L to stabilize the drift current over at least 10 cycles.

$$L > .0024H \tag{3-14}$$

From the example calculation, stiff systems theory is actually a very easy concept to apply. As stated earlier, all you need is a system with at least two time constants. One time constant belongs to the controller, and one time constant belongs to the system that is to be controlled. And the basic idea is that you design either your system or your controller such that the controller has a time constant that is at least 10 times faster than the time constant of the system.

3.4 Complete Hardware Circuit

Figure 3.8 shows a hardware diagram with the buck, the battery, the fuel cell, and the load. The battery is a simple resistor and voltage source in series, labeled R_B and V_B. The inductor shown in the Figure is the same inductor just designed using stiff systems theory. An LR time constant was used to design the inductor, but there are more components that a single inductor and resistor. It is not necessary to include more than the load resistor when calculating the inductor time constant (*L/R*), because the load resistor has the greatest affect on the inductor current. The other components have minimal affect on the rate at which the inductor discharges its current.

The filter capacitor, C_{filt} is optional. That capacitor is not used to stabilize the load voltage – which is its traditional role - because the battery possesses that task. The filer capacitor filers ripple and noise from the inductor current. If the capacitor was not present, then this ripple would also be present in the battery current. The filter capacitor is especially attractive for use with the coulomb counter, because it causes the battery current to be very smooth. Since the capacitor almost eliminates battery current ripple, the coulomb counter is more accurate.

The diode, D2, in Figure 3.8 and is also optional. D2 serves as a protection device. In this thesis we do not consider a regenerative load. But if the load were to reverse the polarity of its voltage or reverse the direction of its current, D2 would protect the hybrid power supply from such violent behavior from the load.

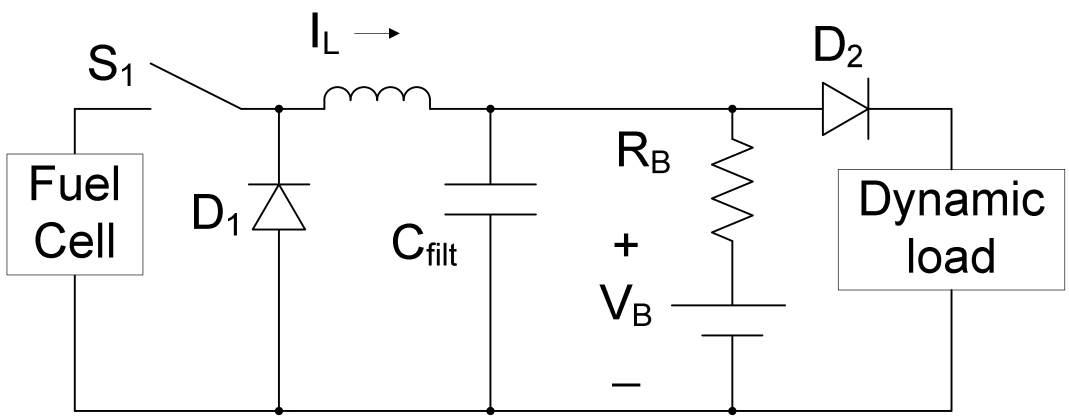

Figure 3.8: Power supply hardware diagram

It is shown in Figure 3.4 that the input current to the buck converter is discontinuous. This implies that the fuel cell current is also discontinuous. An option to reduce the discontinuity in the fuel cell current would be to add a harmonic filter at the input to the buck converter. The harmonic filter will not cause the fuel cell current to be smooth, but it will reduce current ripple. Adding a harmonic filter and employing a fuel cell current tracking control strategy would also not be appropriate, because the current ripple will still be substantial. But the harmonic filter could increase fuel cell lifetime.

CHAPTER IV
PROPOSED CONTROL SCHEME

This Chapter designs two control algorithms for the buck converter's inductor current. One controller is low-level, and it strictly controls the inductor current to track a reference. A high level controller is also designed to calculate the inductor reference current value. By calculating the reference, the high level controller effectively controls the fuel cell's operating point. It is also explained how the high-level controller meets the performance criterion of the power supply and operates the fuel cell in its most efficient region.

4.1 Digital Control

We mentioned in Chapter III that we want the buck converter's inductor current to track a reference, and we described how to design the inductor using stiff systems theory to achieve desired control. Chapter III also mentioned why it is desirable to use the buck as a current source instead of its traditional use as a voltage source.

I experimented with digital PI, digital PID, bang-bang, and fuzzy logic controllers. And fuzzy logic had the best performance at controlling the inductor current with minimal error. So this thesis will not explain PI, PID, or bang-bang control any further, because they are not used. Digital controllers are more attractive than analog control, because inexpensive programmable integrated circuits such as microcontrollers, digital signal processors, programmable logic controllers, or programmable logic arrays can be used. Updating a control algorithm simply means updating the software. If one needs to make changes to an analog controller, then one needs to remove and replace hardware components such as Op-amps. Since digital controllers can utilize programmable devices, they are extremely versatile in the design of their algorithms. In this sense, digital controllers are superior to analog controllers, and that is why digital control is used instead of analog control in this thesis [15].

The two controllers designed in the next section can easily be implemented into one of the programmable devices previously mentioned. Given that modern programmable devices can multi-task, both high-level, and low-level controllers can be programmed into a single integrated circuit.

4.2 Fuzzy Logic Control

The goal of the low-level controller designed in this section is to have the inductor current track a reference value with minimal error, and to reject disturbances in the dynamic load. The buck converter has one degree of freedom which may be adjusted to accomplish current control: the duty cycle.

To be able to control the inductor current using fuzzy logic, the controller only needs to know the reference current, the measured current, and the duty cycle [16]. Figure 4.1 gives the signal flow graph of the fuzzy logic controller. Memory is required in the feedback loop, because it must remember the previously used duty cycle for every switching period. The fuzzy logic controller samples the error as input and the resulting output is a new duty cycle for the buck converter calculated every sampling period. So the fuzzy logic controller is a discrete-time (or digital) controller, because a discrete event occurs every sampling period. The buck converter's switching period is the fastest amount of time that a controller can take any action. Since we want the fuzzy logic controller to respond to system dynamics as fast as possible, the controller sampling period and the buck switching period are the same.

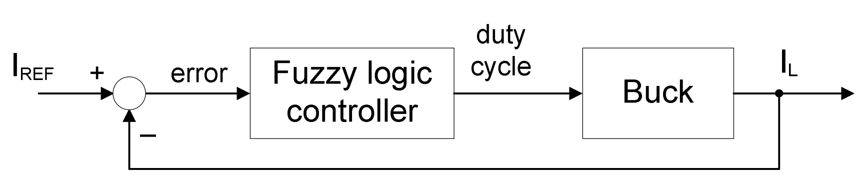

Figure 4.1: Fuzzy logic control signal flow graph

To introduce the fuzzy logic concept, we introduce the definition of error. The inductor current, $I_L[k]$, is sampled periodically: where k is the sampling instant. Error is defined as the difference between I_{REF} and $I_L[k]$, and for every sample time, the error is updated.

$$error[k] = I_{REF} - I_L[k] \tag{4-1}$$

Error is very important for a controller, because a perfect controller has zero error, but perfect controllers are unrealizable for a system with power electronics. The best a practical controller can do is to reduce the error to as little as possible. The fuzzy logic controller designed in this thesis also measures the sign of the derivative of the inductor current. The controller uses the sign of the derivative, because it needs to know if the current is increasing or decreasing. The sign of the derivative is calculated using the following formula.

$$sign\left(\frac{dI_L}{dt}[k]\right) = sign\left(I_L[k] - I_L[k-1]\right) \tag{4-2}$$

Fuzzy logic also uses the following abbreviations.

P = positive	PS = positive small	PB = positive big
N = negative	NS = negative small	NB = negative big

Figure 4.2 can be used to help explain how fuzzy logic achieves the current tracking control objective. The points labeled in Figure 4.2 are designated (sign of error, sign of the derivative of the current). Fuzzy logic in fact does not need to know the exact magnitude of the error or the magnitude of the derivative: as shall soon be shown.

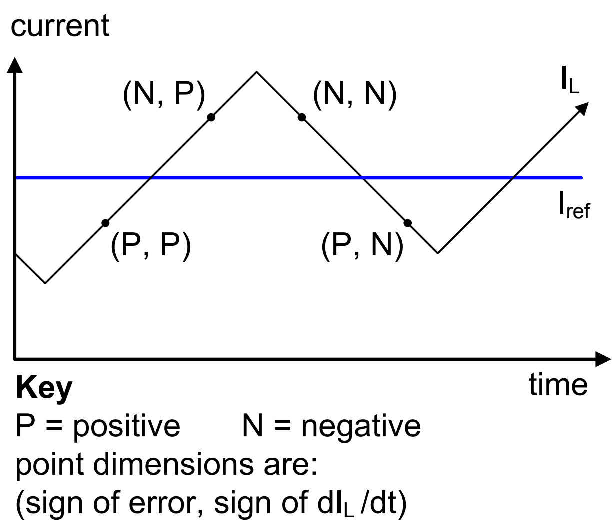

Figure 4.2: Fuzzy logic concept diagram

For point (N, P) in Figure 4.2, the magnitude of the measured current is above I_{REF}, and the measured current is increasing. This means that the measured current is too high, and the magnitude of the error is also increasing. For this case the controller needs to make a big correction in the duty cycle to get the inductor current to track I_{REF} with less error. For point (P, N) the magnitude of the measured current is below I_{REF}, and the measured current is decreasing. This means that the measured current is too low, and the magnitude of the error is also increasing. For this case the controller also needs to make a big correction to the duty cycle.

For point (P, P), the measured current is increasing, but the measured current is less than I_{REF}. That means that the error is decreasing. Even if the controller takes no action, the error could go to zero, and perfect control could be obtained for an instant. So if the controller makes a correction, only a small correction would be necessary. Point (N, N) is also a case where if any correction is made, then only a small correction in the duty cycle is necessary.

Table 4.1 takes these same concepts illustrated in Figure 4.2, and puts them into an algorithm. When the inductor current needs to be increased, then the duty cycle is also increased. But the fuzzy controller makes a big increase or small increase depending on the sign of the derivative. Likewise, when the inductor current needs to be decreased, the duty cycle is also decreased, and the amount depends on the sign of the derivative.

Table 4.1

Fuzzy logic table for controlling the inductor current

error[k] \ $\frac{di}{dt}[k]$	P	N
P	PS	PB
N	NB	NS

Fuzzy logic does not measure the exact magnitude of the error or the magnitude of the derivative of the current; the controller used in this thesis is designed only to consider the sign of each. The magnitude of the derivative of the current can be complicated to calculate for discrete time systems, and it's unnecessary for this controller. In Chapter VI, the performance of the fuzzy logic controller described in table 4.1 is shown. The performance is very good - knowing only the signs of the error and the derivative.

How much should the sizes of positive big, positive small, etc… be? Sizes of each that give good results were determined through trial and error. There is no method of exactly calculating the optimal sizes of positive big, positive small, etc… Exact numbers used in the simulations of this thesis are given in the parameters section of Chapter V. So with fuzzy logic, nothing is calculated with exact precision; that is why it is called "fuzzy" logic. But the fuzzy logic controller achieved better results than PI or PID control. The MATLAB code for the fuzzy logic controller used in the simulations for this thesis is in Appendix A.

This controller is low-level because it does not need to look at the overall behavior of the power supply of the load. In fact, this fuzzy logic controller is oblivious to much of what may be occurring in the system. The fuzzy logic controller only knows if the inductor current is tracking the reference value with minimal error. There is much more phenomena occurring in the system that also needs to be monitored, so the high level controller designed in the next section addresses these issues.

4.3 Overall System Level Control

Referring back to Chapter I, one major advantage of hybrid power supplies is the ability to store excess power. The power supply's control should be designed such that the fuel cell delivers average power and the battery delivers peaking power. We also want the fuel cell to deliver power at its most efficient operating point as often as possible. So that means the fuel cell must be designed such that the average power is also the most efficient operating point for the fuel cell. The fuel cell will be the main energy source. The battery will be used for load leveling. So when the load power demand is less than average, we want excess power from the fuel cell to charge the battery, and when load power is above average we want the battery to the battery to discharge the extra power that is needed.

Figure 4.3 shows a dynamic load not unlike a load that the power supply designed in this thesis would have to serve. In the top graph, the blue curve is instantaneous power, and the red line is the average power over time. Under dynamic load situations such as the dynamic load in Figure 4.3, we would want the fuel cell to deliver average power: that is the red line in the top graph. Notice that the dynamic power curve on the bottom has an average of zero. We would want the battery to deliver the dynamic power or peaking power, and the battery's average power will be zero. It makes sense for the battery's average power to be zero, because the battery cannot effectively deliver a net power over an extended period of time. The battery is a storage device. The battery can only store excess power from the fuel cell and release its stored energy when the load demands it. The fuel cell is the main power source that delivers net power to the load.

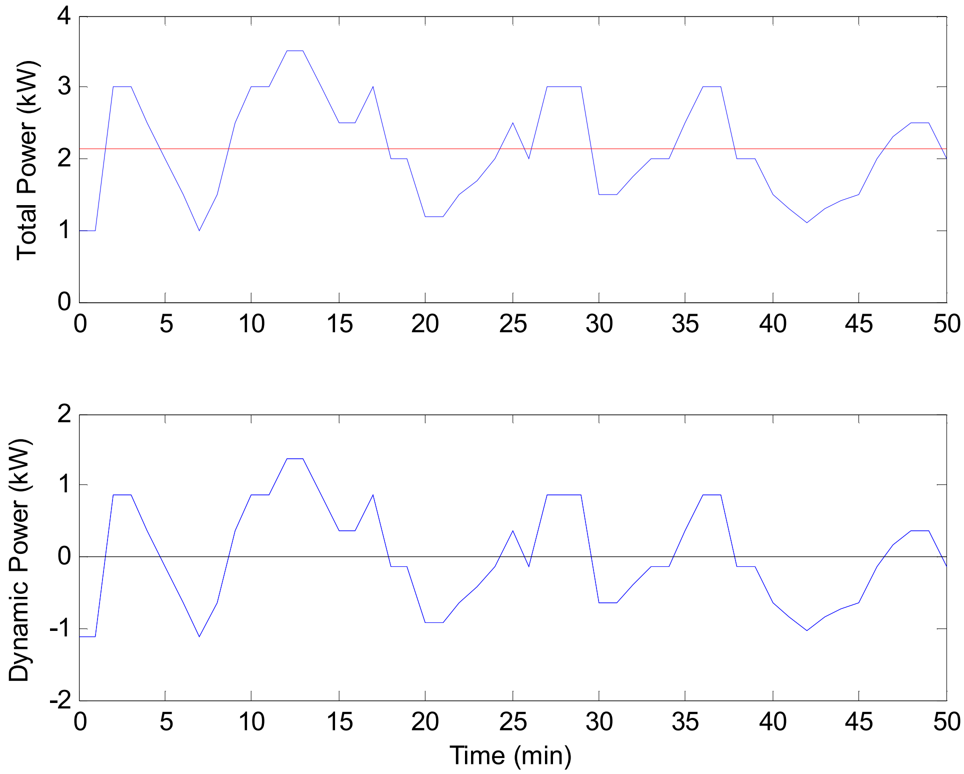

Figure 4.3: An arbitrary dynamic load, average power, and dynamic power

A high-level controller that monitors many parts of the system needs to be designed to have the hybrid power supply serve a load like the one in Figure 4.3. A controller that causes a variable to track a reference cannot achieve desired system-level performance previously described. The high-level controller needs to know how the system is behaving as a whole; that is why the high level controller needs to monitor more than just a single variable. The high-level controller can be designed to make its assertions about the entire system based on the several variables it monitors.

The high level controller will use I_{REF} as its degree of freedom to achieve desired system-level performance. And the low-level fuzzy logic controller designed in section 4.2 will do its job without knowing anything that the high-level controller is doing. And the fuzzy logic controller does not need to know how the system as a whole is performing. The high-level performance criterion is tabulated below

Table 4.2

High-level performance criterion

Monitor SOC such that the battery will always readily accept charge or have stored energy to discharge when the load suddenly changes
Load voltage must be regulated within a window of a minimum and maximum
The battery current cannot exceed a threshold when charging or discharging in order to protect the battery
The fuel cell should operate in its most efficient operating region as often as possible to conserve fuel usage

To achieve the above performance criterion, the high-level controller needs to monitor 4 things in the system: battery SOC, battery current, load voltage, and the fuel cell's operating point. The high level controller will be designed to regulate all 4 of these variables with only one degree of freedom: I_{REF}. But it is impossible to regulate all 4 variables simultaneously, because we have only one degree of freedom. So the controller employs a multiplexing technique to sample one variable at a time. The controller would then adjust I_{REF} to service the variable that was just sampled according to the performance criterion. Each variable is on rotation in a queue, and all variables will be serviced in the order of their queue before the controller services a variable again.

For the controller to achieve the performance objectives in table 4.2, they need to be quantized into a set of rules so that a program can be written to implement them. Table 4.3 breaks down the set of four high-level objectives into seven rules. These rules are numbered precisely, because this is the order in which the rules are serviced in their queue.

Table 4.3

Rules for adjusting I_{REF}

(1) If $V_{load} > V_{max}$, decrease I_{REF}
(2) If $V_{load} < V_{min}$, increase I_{REF}
(3) If $I_{batt} > I_{batt\ max}$, increase I_{REF}
(4) If $I_{batt} < -\lvert I_{batt\ max}\rvert$, decrease I_{REF}
(5) If SOC > 90% , decrease I_{REF}
(6) If SOC < 60% , increase I_{REF}
(7) If all above rules are met, and if the fuel cell is not operating in its optimum efficiency region, then the following: If $I_{REF} > I_{OPTIMAL}$, decrease I_{REF} If $I_{REF} < I_{OPTIMAL}$, increase I_{REF}

The rules in table 4.3 basically quantize the performance criterion in table 4.2. The power supply is designed to give a regulated DC voltage to a load, so it is natural to assume that the load voltage must fall between a narrow band of a minimum and a maximum. The battery's current must be limited when charging or discharging to avoid overheating and possibly burning the battery. Keeping the battery SOC between 60 - 90% ensures that it will always readily accept or deliver charge; i.e. the battery must ensure uninterrupted power delivery. If the rules (1) through (6) are all satisfied, then we want the fuel cell to be operating in its most efficient operating region. If any of the rules (1) through (6) are not satisfied, then the condition for rule (7) can be relaxed temporarily, because those six rules are more important for safety.

Safety is more important than a temporary disregard for fuel conservation. Say one rule was unsatisfied and the fuel cell was no longer operating most efficiently. Then say the load conditions change and rules (1) through (6) are satisfied again, then the controller will bring the fuel cell's operating point back to the most efficient region. Having the fuel cell deliver power efficiently as often as possible means that the fuel cell delivers power efficiently as often as conditions of the power supply are safe.

The rules in table 4.3 decide either to increase or decrease I_{REF}; but by how much and how fast? The high-level controller needs to adjust I_{REF} at a rate that the fuel cell can follow. The fuel cell has a time constant of about 30 seconds. That means the fuel cell takes 30 seconds to warm up to deliver power from zero to its optimum power (most efficient power). So the high-level controller needs to be consistent with this slow dynamic response time, because this controller is effectively controlling the fuel cell's power. The high level controller cannot request for the fuel cell to change its output power faster than the fuel cell's capability. So the high level controller services one of the rules in table 4.3 every .5 seconds. That means all seven conditions to be tested in table 4.3 are serviced every 3.5 seconds in their specified order. If I_{REF} needs to be increased or decreased, then the change is ± .5Amps. I chose .5 Amps as the step size because the fuel cell is only able to adjust its power output by a small amount in .5 seconds.

The flowchart in Figure 4.4 takes the rules in table 4.3 and puts them together into an algorithm that a programmer can write. The flowchart also adds a startup routine, but it is not complicated. The startup routine simply starts I_{REF} at zero and increases I_{REF} by .5Amps every .5 seconds until the converter power is operating at its most efficient point. The flowchart might look daunting to somebody who is not an experienced programmer, but it does not include any more details than the seven rules previously described, and the simple startup routine. The flowchart shows how each variable is serviced one at a time in the same order presented in table 4.3. The program acts as an infinite loop that repeats itself every 2 seconds.

Notice that when one of the rules (1) through (6) is not satisfied, then the flowchart remembers that a violation occurred. When it comes time to check the fuel cell's efficiency and if a violation occurred, then the algorithm will bypass the efficiency

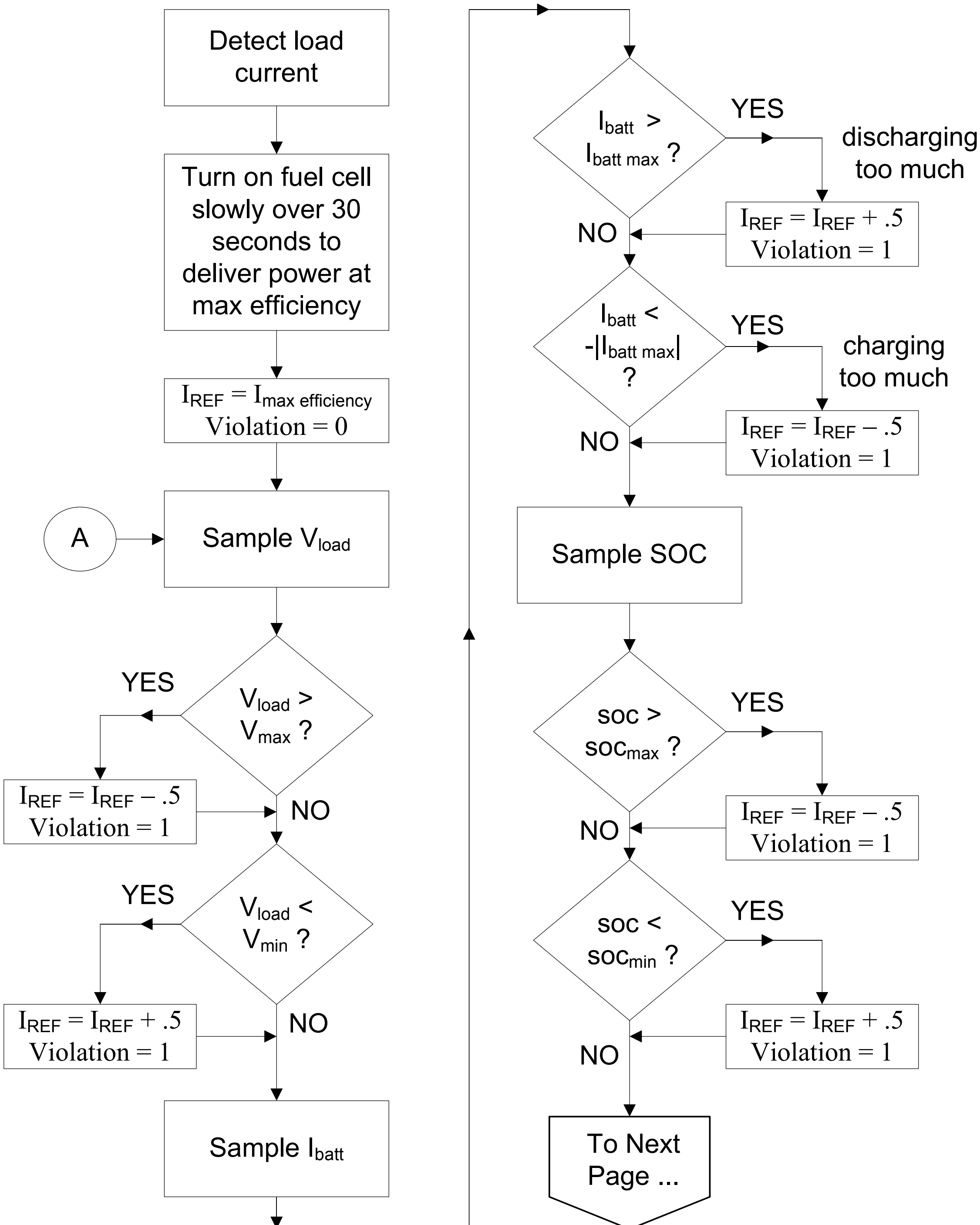

Figure 4.4: High-level control flowchart

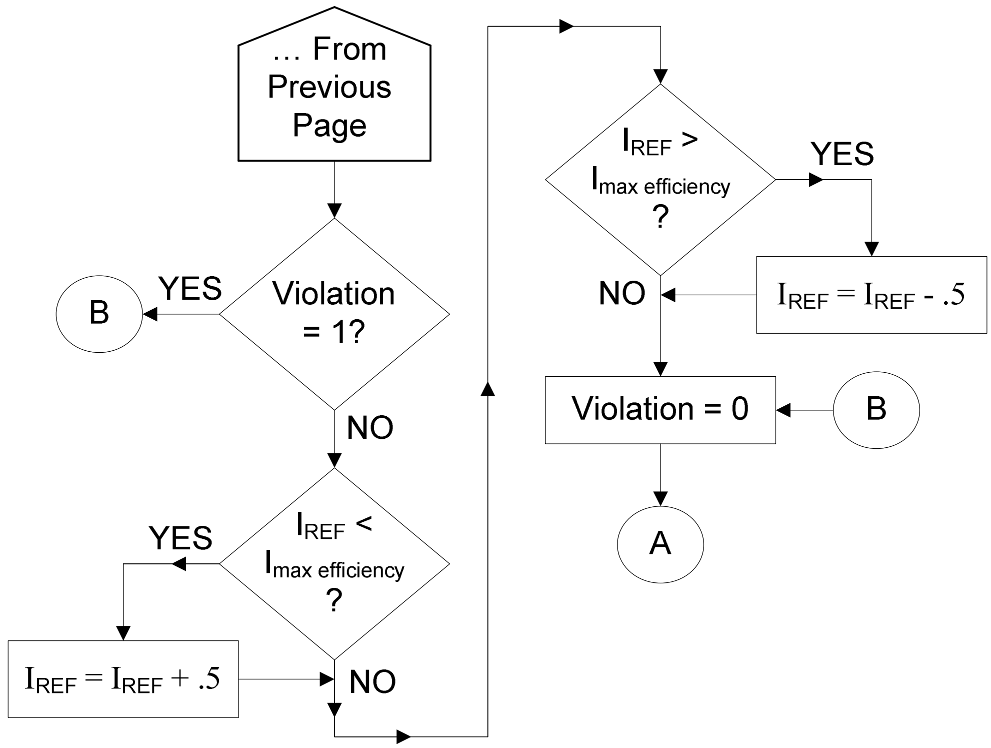

Figure 4.4: Continued

constraint, and the queue will be reset. The high-level control algorithm starts over again. The MATLAB code to implement the high-level control algorithm is in Appendix B.

Figure 4.5 shows the complete hardware diagram with all of its sensors. There is a sensor for the inductor current, a sensor for the battery current, and a sensor for the load voltage. To monitor the battery's SOC, only the battery current sensor is needed, because the SOC can be determined by coulomb counting. The current sensor in series with the inductor is very important, because that sensor is essential to operating the buck as a current source. And the placement of that current sensor is new to this thesis. This current sensor is also very important, because it is an improvement claimed in this thesis built off of previous authors' works mentioned in Chapter I.

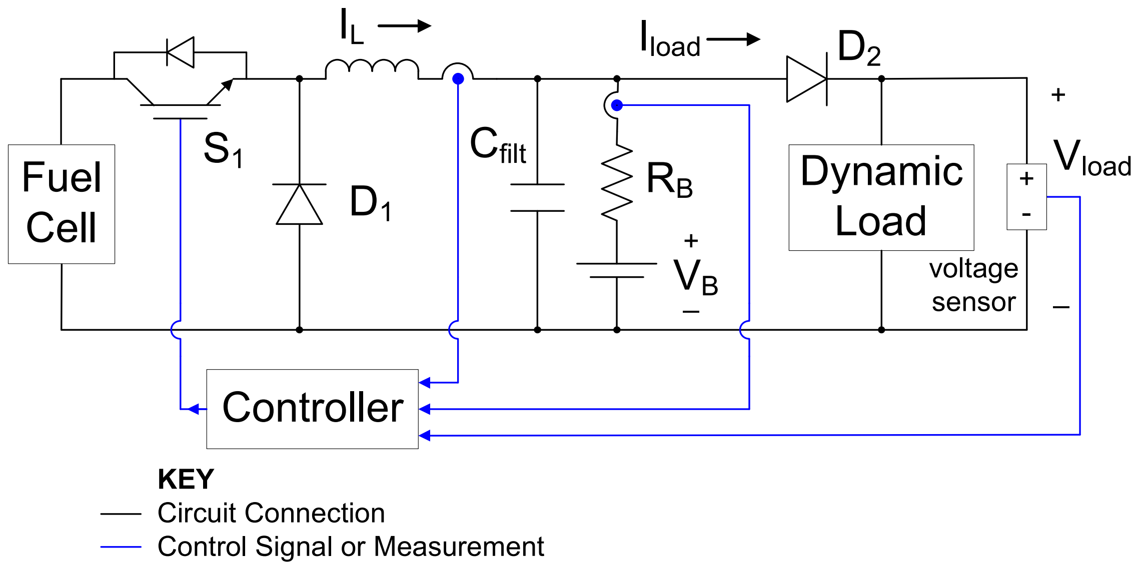

Figure 4.5: Complete circuit diagram with sensors and controller

Figure 4.6 shows the how the high-level and fuzzy logic controllers work together. And you can see how the signal flow graph compliments the circuit diagram above.

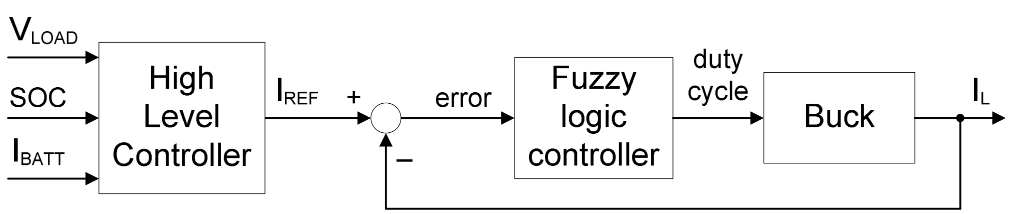

Figure 4.6: High-level control signal flow graph

CHAPTER V
SIMULATION MODELS

In this chapter, the Simulink models to conduct the simulations are presented. The significance of important blocks is explained. Some of the blocks have embedded MATLAB code, and the code for those blocks is presented in the appendices. The simulation parameters are given at the end of the chapter.

5.1 Simulation Hardware Models

Figure 5.1 is basically a Simulink model of the hardware diagram in Figure 4.5.

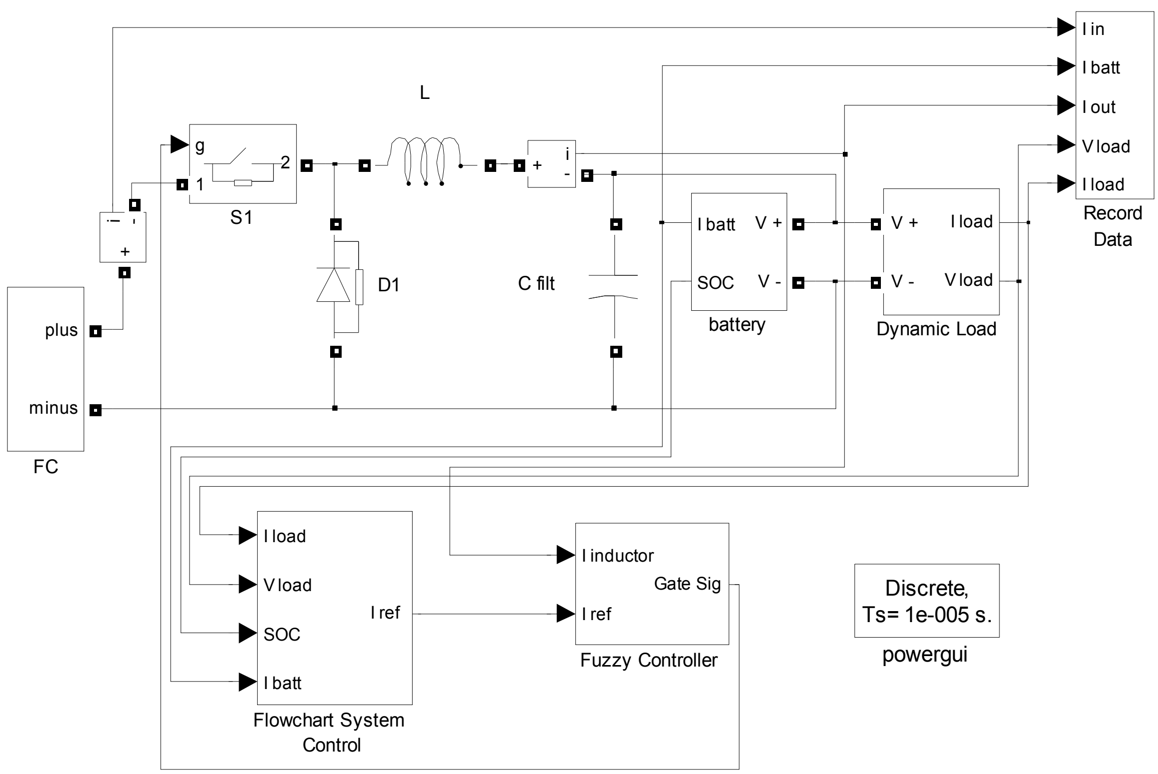

Figure 5.1: Overall Simulink model

You can see the components of the buck converter, the fuel cell, the battery, the controllers, and the dynamic load in both Figure 5.1 and Figure 4.5. The fuzzy logic and the high-level flowchart controller blocks are also obvious. As explained in Chapter IV,

The only degree of freedom that the fuzzy logic controller has is the duty cycle for the transistor. The duty cycle is not a direct output of the fuzzy logic controller, but the transistor's gate signal is. And the gate signal carries the duty cycle that the fuzzy logic controller generates. Figure 5.2 is just a Simulink version of the fuel cell equivalent circuit shown in Chapter II. This circuit is the subsystem labeled "FC" in Figure 5.1.

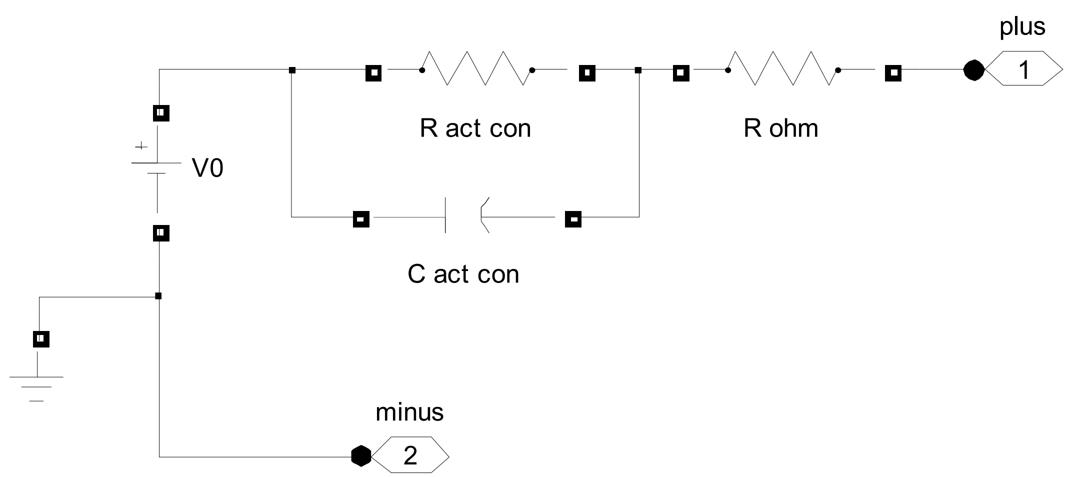

Figure 5.2: Simulink model of the fuel cell

For a dynamic load, a parallel combination of resistors with switches is used as in Figure 5.3. The user determines the times at which the switches open and close, and the equivalent resistance of the parallel combination of the load resistors changes as each switch opens or closes. The switching behavior in effect creates a resistive load that varies with time, and this combination of switches and resistors serves as the dynamic load. The two load profiles that will be presented in Chapter VI were created using this same model - but with different switching times for the transistors.

The battery model in Simulink is just a resistor in series with a voltage source: just like the battery equivalent circuit shown in Chapter II. Figure 5.4 is the battery and coulomb counter subsystem block that is labeled “battery” in Figure 5.1. The battery subsystem measures the battery current and SOC and gives this data to the high-level controller block.

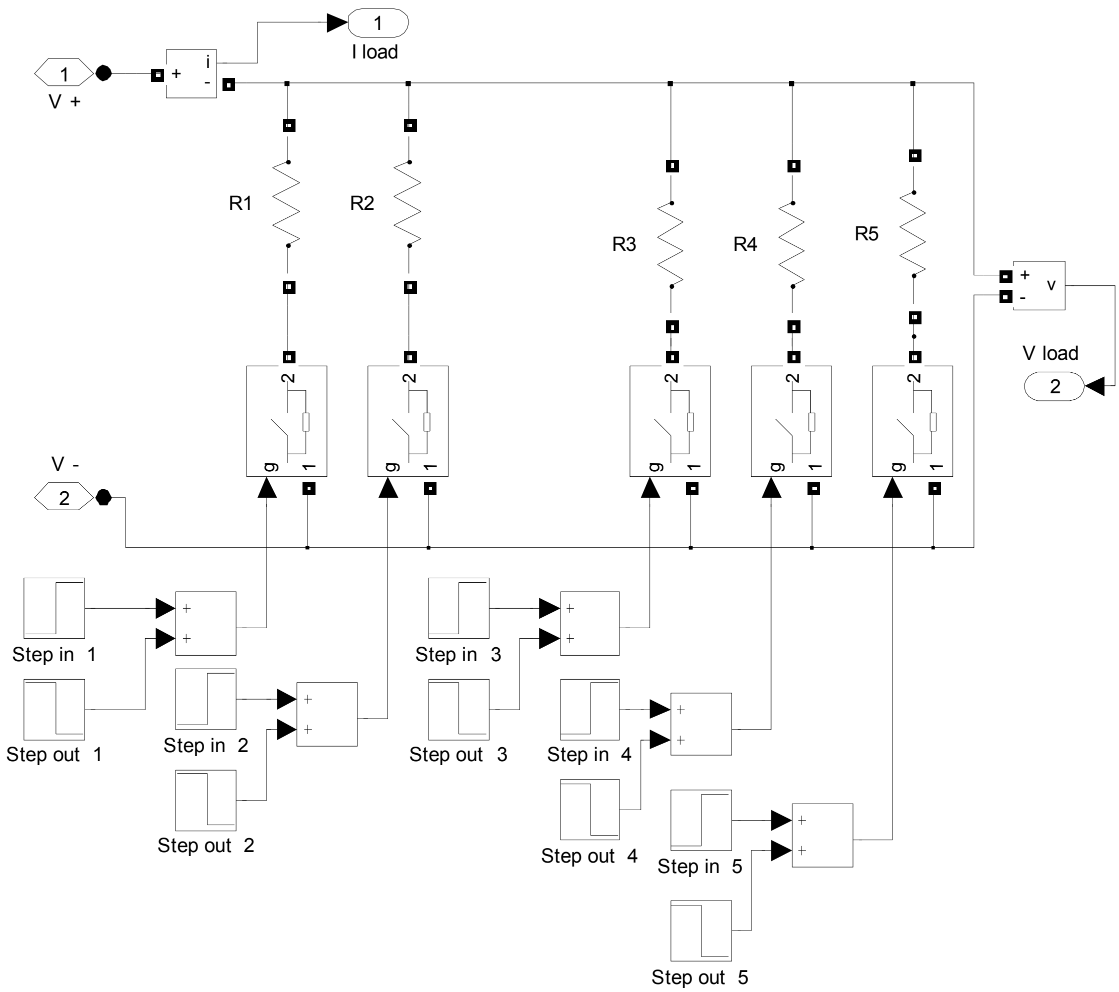

Figure 5.3: Dynamic load subsystem

The block labeled “Coulomb Counter” in Figure 5.4 is in fact another subsystem. This subsystem shown in Figure 5.5 contains an embedded MATLAB function that estimates the battery’s state of charge when given the battery current, battery Ah rating, initial SOC, and the coulomb counter's sampling period as inputs. This function uses the same techniques for coulomb counting presented in Chapter II. The code used in the embedded block in Figure 5.5 is presented in Appendix E. The coulomb counter function samples the battery current at a frequency of 50k Hz.

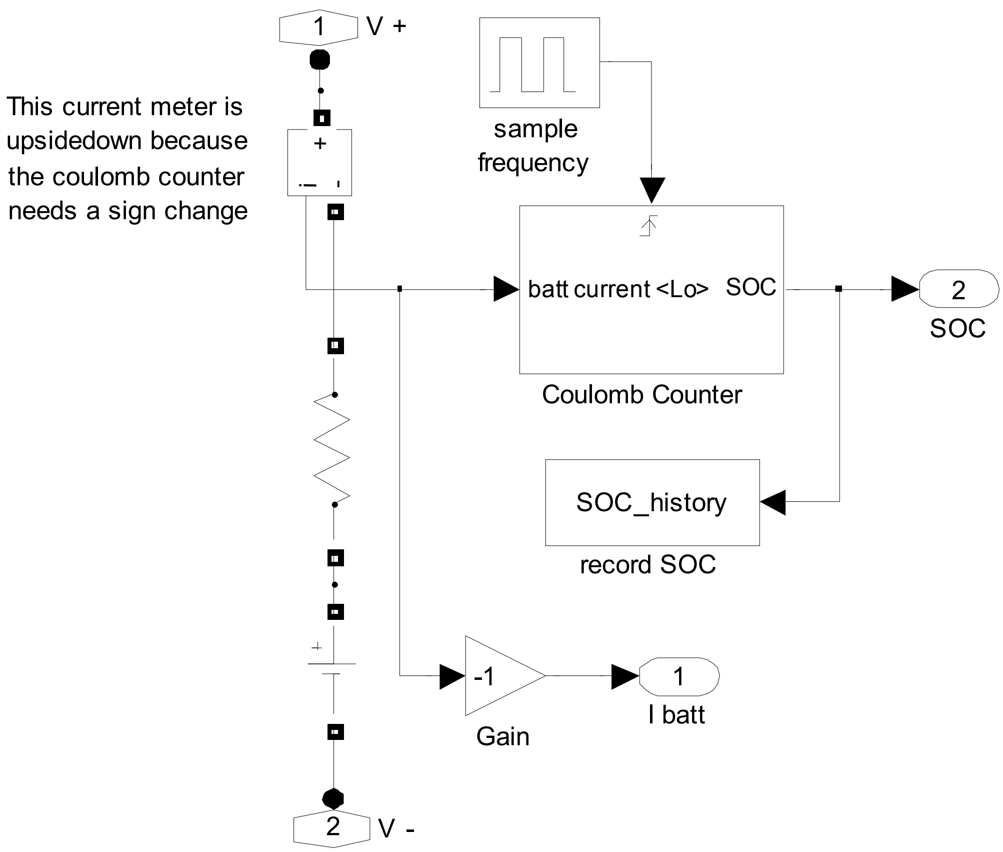

Figure 5.4: Battery model and coulomb counter subsystem

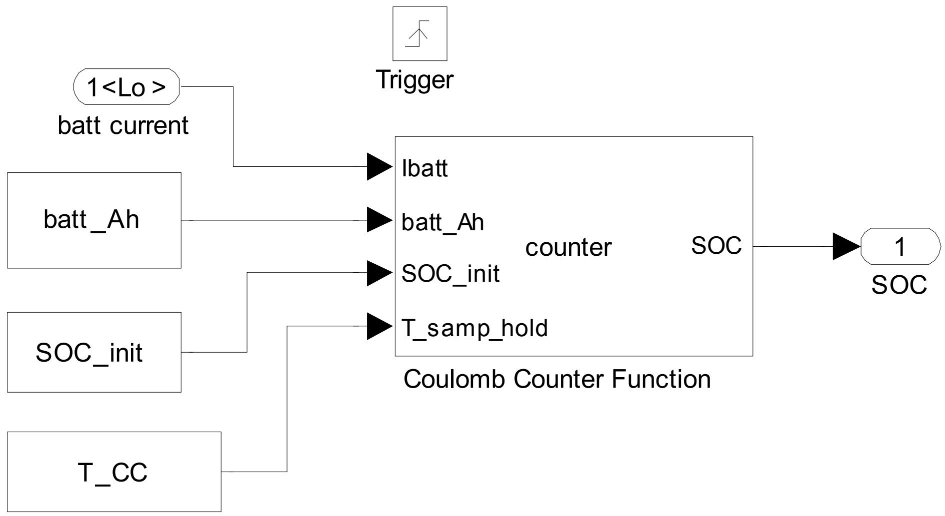

Figure 5.5: Coulomb counter embedded MATLAB block

5.2 Simulation Controller Models

Looking at Figure 5.1, there are two control subsystems; one is labeled “Flowchart System Control,” and one is labeled “Fuzzy Controller.” You can see that the output of the flowchart controller is the reference current value used as an input for the fuzzy controller. Figure 5.6 shows the fuzzy controller subsystem. As discussed in Chapter IV, the fuzzy logic controller only needs to know the reference current and the measured current to be able to operate. The block labeled “square wave generator” in Figure 5.6 generates the gate signal for the transistor in the buck converter. The fuzzy logic controller gives a new duty cycle to the square wave generator every switching period, and the square wave generator generates a new gate signal with the new duty cycle. The MATLAB code that implements the square wave generator is in Appendix D. Figure 5.7 is the embedded MATLAB block containing the fuzzy logic software. The fuzzy logic function recalculates the duty cycle for the buck converter at a frequency of 10k Hz: the same as the switching frequency of the buck. The fuzzy logic code is presented in Appendix A, and this code implements the algorithm described in the fuzzy logic table in Chapter IV.

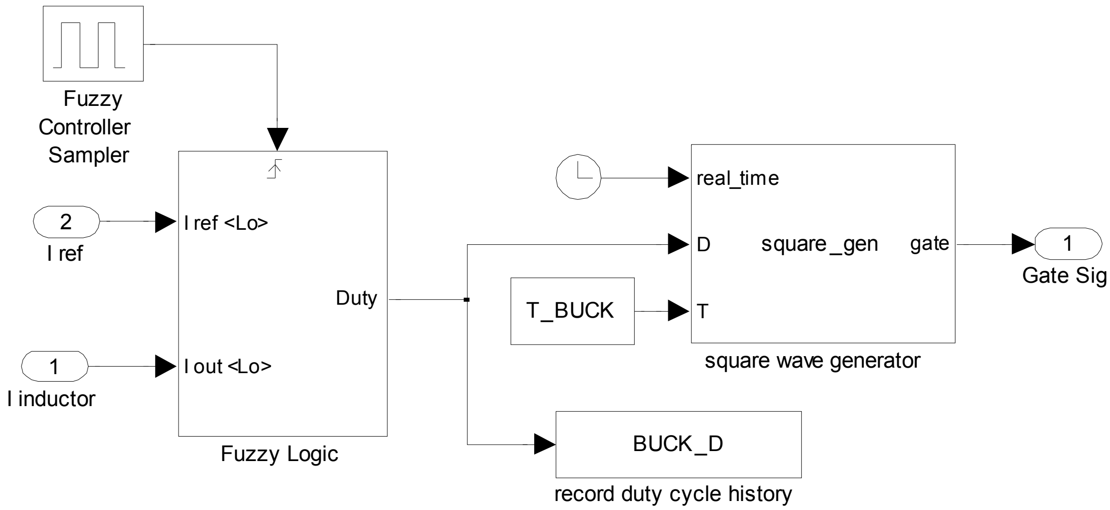

Figure 5.6: Fuzzy controller subsystem

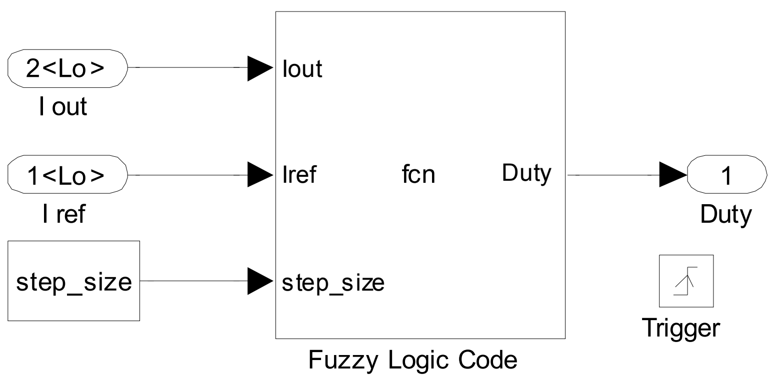

Figure 5.7: Fuzzy logic embedded MATLAB block

Figure 5.8 is the high-level flowchart controller subsystem. As described in Chapter IV, the high-level controller monitors 4 things in the power supply: the battery current, battery SOC, load voltage, and fuel cell efficiency. You can see that the load voltage, SOC, and battery current are inputs to the controller. The load current is an input, because when the controller detects that the load is turned on, it knows to initiate the fuel cell's start-up routine. Once the fuel cell has started, the high-level controller ignores the load current after that. But an input for the fuel cell's efficiency is not an input to the controller. That is because the efficiency is not directly measured. The high level knows the most efficient operating point of the fuel cell, and it is declared as a constant in the program. This high level controller is called at a frequency of 2 Hz, and every time it is called, the controller only samples one of its inputs: just as discussed in chapter IV.

Also the block labeled "flowchart Controller" in Figure 5.8 is an embedded MATLAB function. This function shown in Figure 5.9 does everything that the high-level controller does: as discussed in Chapter IV. The code for the high-level controller is in Appendix B.

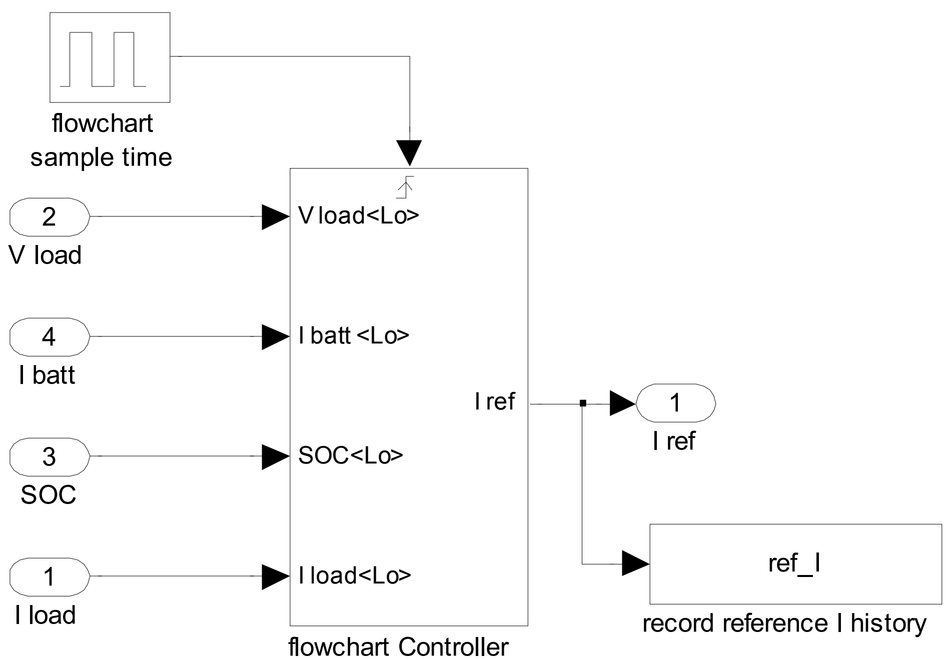

Figure 5.8: Flowchart subsystem

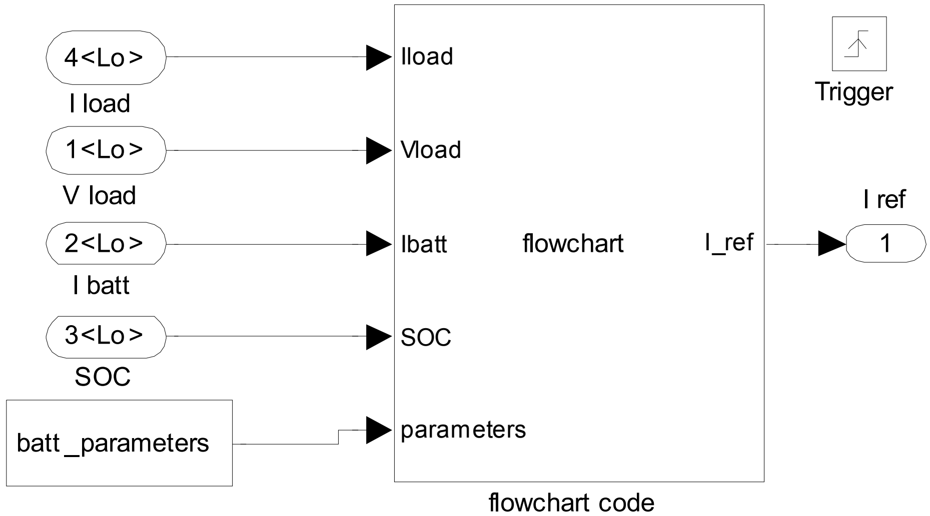

Figure 5.9: Flowchart embedded MATLAB block

5.3 Simulation Parameters

The simulation parameters for the hardware components and controller are presented in the following tables. The MATLAB code that defines all of these parameters is in Appendix C. All of the Simulink models shown previously in this chapter use these parameters defined by this MATLAB code. The power supply design specifications are given in table 5.1. Table 5.2 gives the controller, buck components, and power supply parameters used in the simulations.

Table 5.1

Power supply design specifications

Design Specification	Value	Units
Load voltage	70 ± 5%	V
Fuel cell optimal power	2000	W
Battery rated power (charge and discharge)	1000	W
Load rated power	3000	W
Load average power	2000	W

Table 5.2

Hardware and control simulation parameters

Parameter Name	**Label in MATLAB code and Simulink**	**Value**	**Units**
buck frequency	`f_BUCK`	10	kHz
buck switching period	`T_BUCK`	0.1	msec
fuzzy logic sample frequency	`control_f`	10	kHz
fuzzy logic sample period	`control_T`	0.1	msec
high-level controller sample frequency	`flowchart_f`	2	Hz
high-level controller sample period	`flowchart_T`	0.5	sec
coulomb counter frequency	`f_CC`	50	kHz
coulomb counter sampling period	`T_CC`	20	μsec
fuzzy logic adjustment step size	`step_size`	0.001	duty cycle
nominal load voltage	`v_batt`	70	V
minimum load voltage	`V_load_min`	73.5	V
maximum load voltage	`V_load_max`	66.5	V
inductor size	`BUCK_L`	10	mH
filter capacitor	`C_filt`	3.6	mF

The parameters used for the fuel cell equivalent model in Figure 5.2 and battery circuit model in Figure 5.4 are given in table 5.2. The optimal current given in table 5.3 is the reference current for the inductor to cause the fuel cell to operate most efficiently. It is not the value of the optimal fuel cell current. Recall that the fuzzy logic controller does not cause the fuel cell current to track a reference, because the fuel cell current is discontinuous. When the inductor current is tracking this optimal reference value of 28A, the buck converter power is 2kW. This implies that the fuel cell's power would also be 2kW, because the buck converter losses are negligible. So when the buck is delivering 2kW, it implies the fuel cell is operating most efficiently.

The fuel cell's ohmic resistance and activation and concentration resistance were approximated from the typical fuel cell I-V curve shown in Chapter II. The fuel cell activation and concentration capacitance was chosen to give the fuel cell reaction a time constant of 30 seconds. The battery resistance was chosen to reflect the current and voltage behavior of a Nickel-metal-hydride (NMH) battery. A NMH battery's voltage changes very little even when the battery's current changes substantially. The maximum battery current of 15A would give the battery a maximum power rating of 1kW.

Table 5.3

Fuel cell and battery simulation parameters

Parameter Name	**Label in MATLAB code and Simulink**	**Value**	**Units**
battery voltage	V_batt	70	V
battery resistance	R_batt	0.15	Ω
battery amp hour rating	batt_Ah	6.5	Ah
battery maximum current (charge and discharge)	I_batt_max	15	Ah
battery maximum SOC	SOC_max	90%	% charge
battery minimum SOC	SOC_min	60%	% charge
battery initial SOC for load #1	SOC_init	75%	% charge
battery initial SOC for load #2	SOC_init	60%	% charge
fuel cell maximum voltage	V0_FC	200	V
fuel cell ohmic resistance	R_ohm_FC	1.41	Ω
fuel cell activation and concentration resistance	R_act_FC	1.41	Ω
fuel cell activation and concentration capacitance	R_act_C	21	F
optimal current for the inductor	I_optimal	28	Ah

CHAPTER VI
SIMULATION RESULTS

This chapter presents the results of the simulation models explained in Chapter V. Two different load scenarios were given to test the robustness of the controller designed in this thesis. The significance and insight behind the results will also be explained. The parameters used in both simulations are presented in Chapter V.

6.1 Simulation Results for Dynamic Load 1

This load begins the simulation with a cold start for the fuel cell. The fuel cell's power starts at zero, then it takes 28 seconds to warm up and deliver power at optimal efficiency. This first load profile is shown in figure 6.1. It is chosen to show how the controller behaves under favorable conditions, because it does not cause the performance criteria to be violated. The load profile stays between ~1kW and ~3kW. If the load demand stays within this window, then this is favorable for the power supply, because the average power is about 2kW: which is the optimal power for the fuel cell.

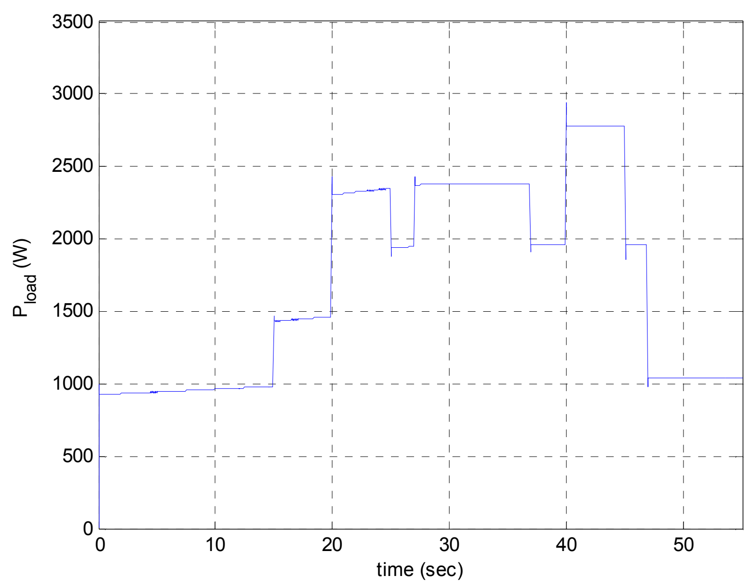

Figure 6.1: Dynamic load profile #1

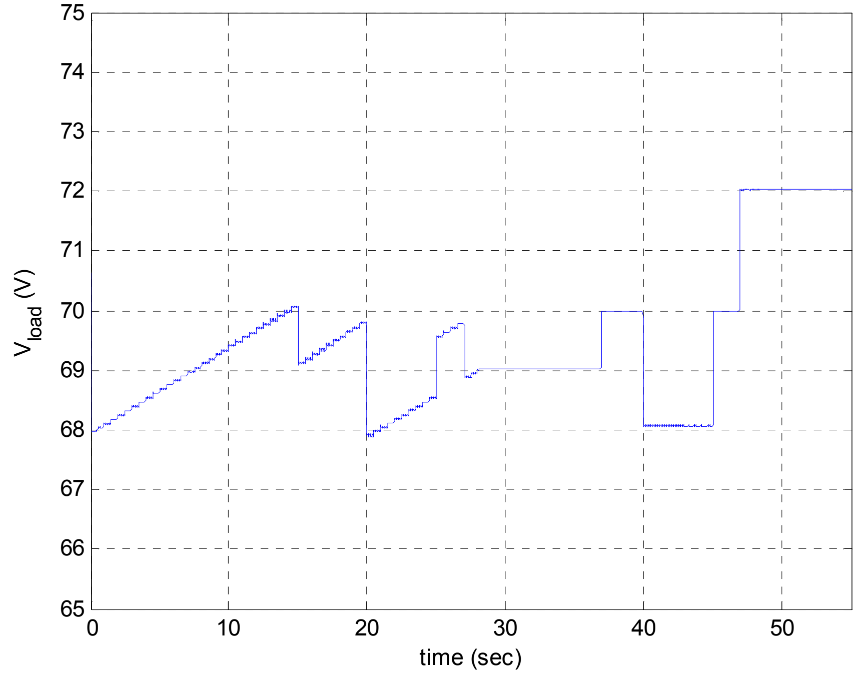

Figure 6.2: Load voltage profile #1

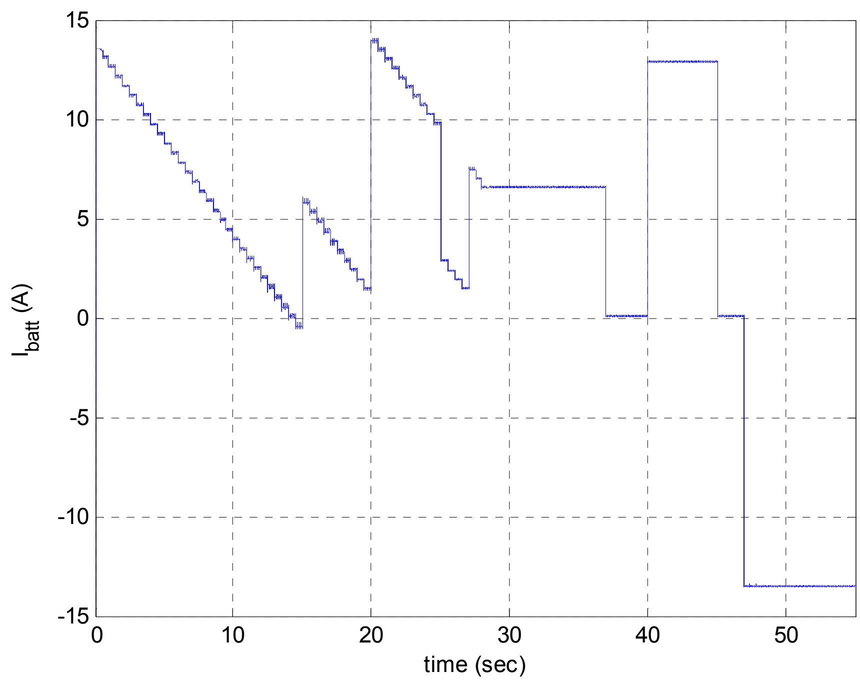

Figure 6.3: Battery current #1

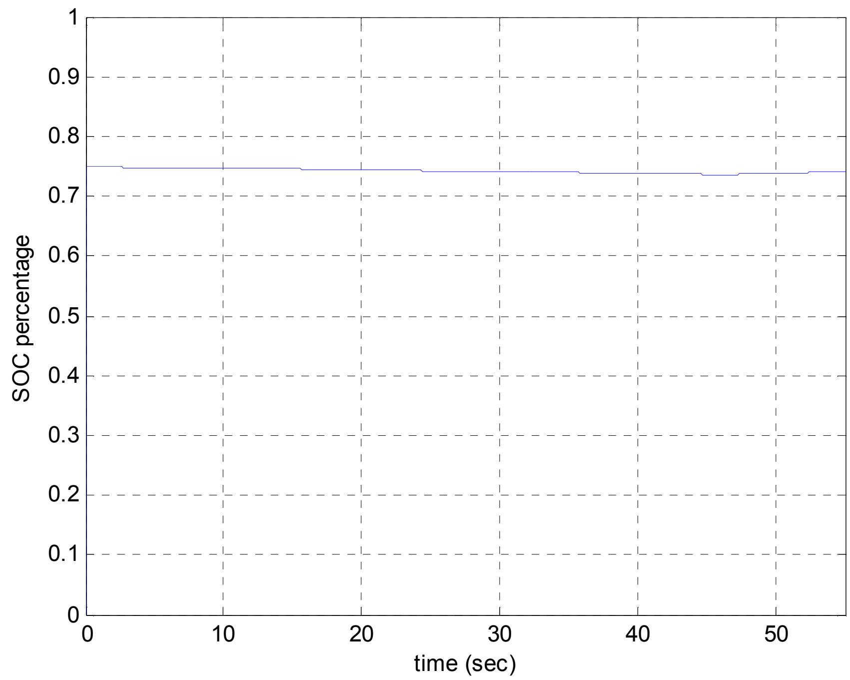

Figure 6.4: Battery SOC #1

You can see in Figure 6.2 that the load voltage stays within 70V ± 5%; the load voltage is also the battery voltage. And Figure 6.3 shows that the battery current is also within ±15A. In figure 6.4, the SOC of the battery does not go outside the boundaries of 60% - 90%. So that means after the fuel cell warms up, the controller can keep the fuel cell operating at the optimal efficiency throughout the duration of the simulation.

Figure 6.5 shows that the output power of the buck converter stays at about 2kW as expected. The small variations shown in the output power are due to the variations in the battery voltage. Figure 6.6 shows that the battery power is also within the window of ± 1kW. This is favorable because the battery is rated at 1kW charging and discharging, and the power supply's design criteria has the battery deliver peaking power of ± 1kW.

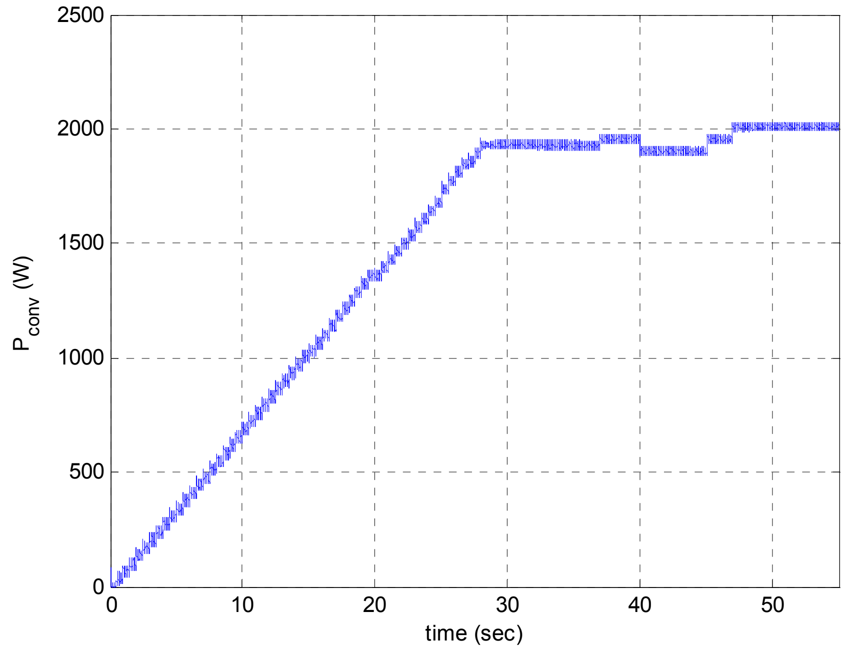

Figure 6.5: Converter output power #1

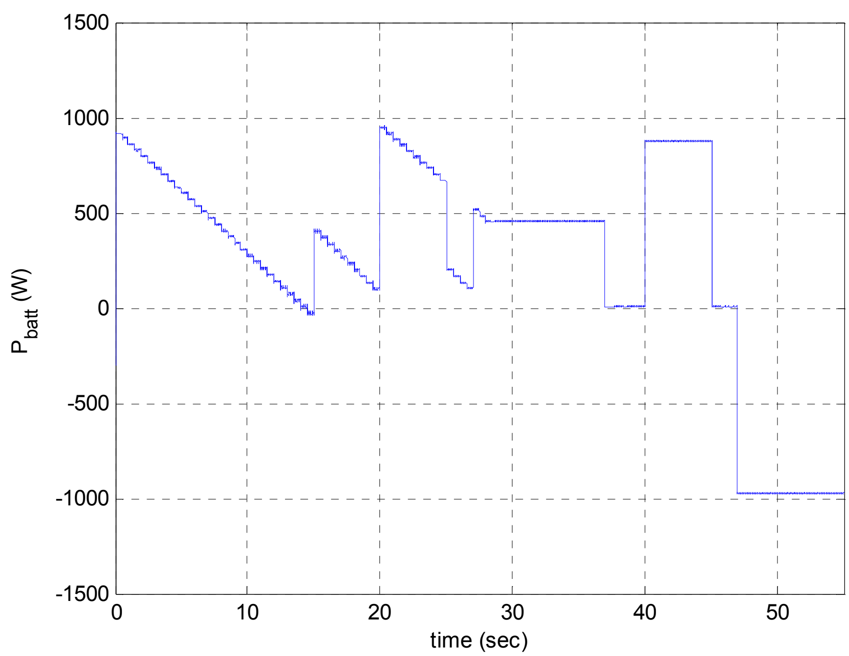

Figure 6.6: Battery power #1

Figure 6.7 shows the reference current produced by the high-level controller. The high-level controller gives the fuel cell 28 seconds to warm up (which is also shown in Figure 6.5). But once the fuel cell reaches its optimal power, the high-level controller does not make any adjustments to the reference current value, because the performance criteria are all satisfied.

Figure 6.8 shows the measured inductor current. You can see that the current ripple is ± .5A for any reference value. That means that the fuzzy logic controller has very good performance at making the inductor current track its reference value. This means that the fuzzy logic controller makes the buck converter behave like a very good current source. Such good performance is the reason why a fuzzy logic controller was chosen for current tracking control over other controllers: such as a PI, PID, or bang-bang controller. Figure 6.9 shows the duty cycle calculated by the fuzzy logic controller, and it converges to a steady state value as expected. The noise in the duty cycle that occurs after 15 seconds is due to a sudden increase in load power demand.

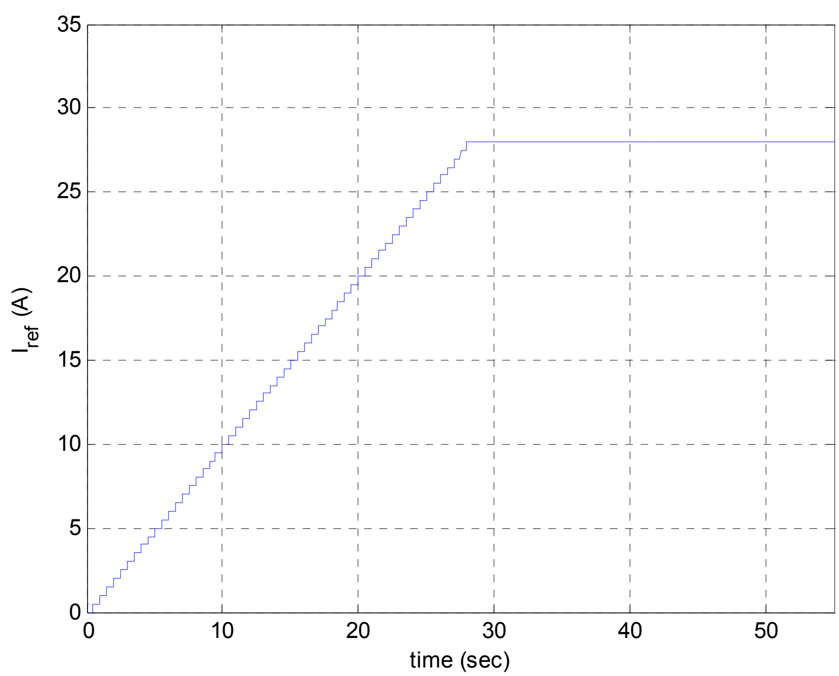

Figure 6.7: Reference current #1

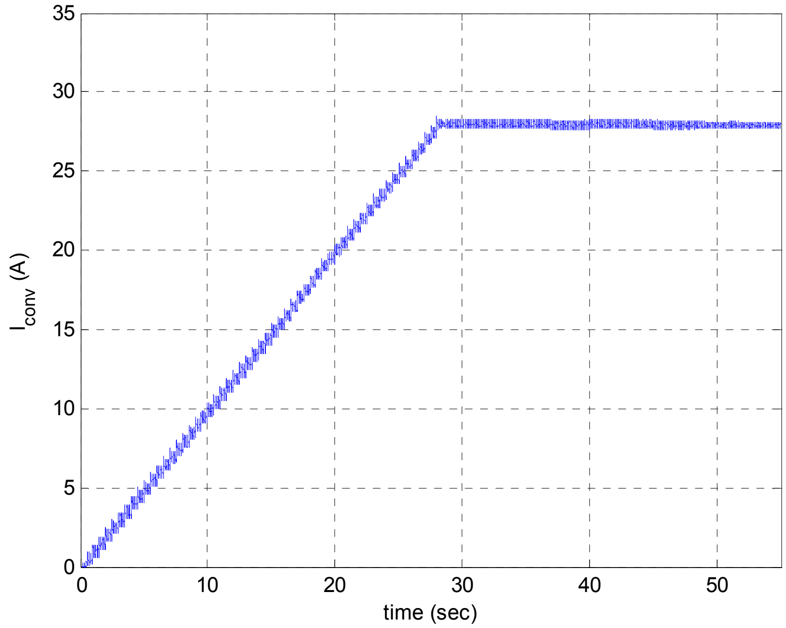

Figure 6.8: Inductor current #1

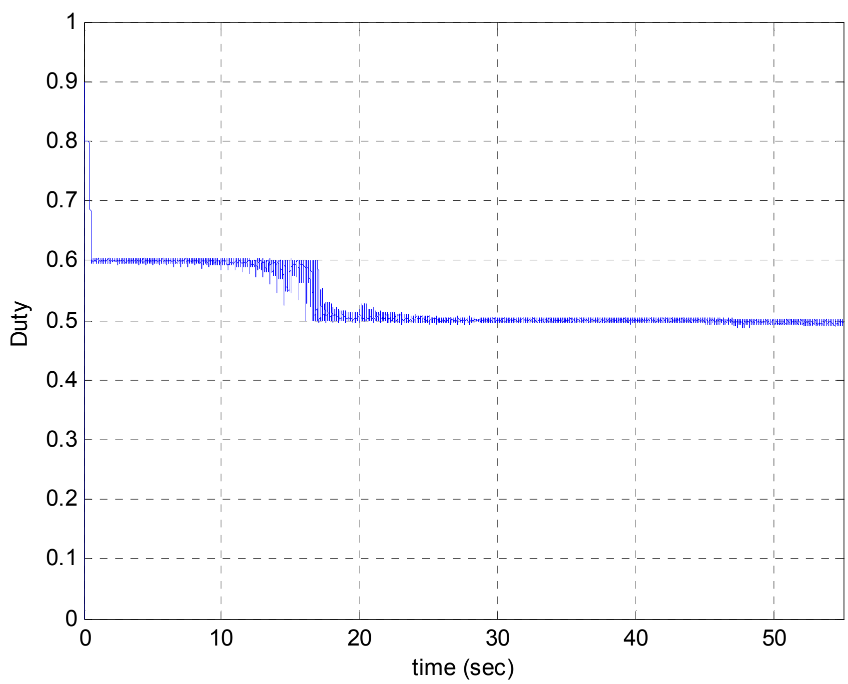

Figure 6.9: Fuzzy logic duty cycle #1

Figure 6.10 shows the fuel cell current. This is also the current that is the input to the buck converter. The bottom graph is a zoomed-in window of the fuel cell current to show that the current is discontinuous. Even though the fuel cell current is discontinuous, the average power of the fuel cell at steady state is 2kW. You can see in the bottom graph why it does not make sense to have the fuel cell current track a reference.

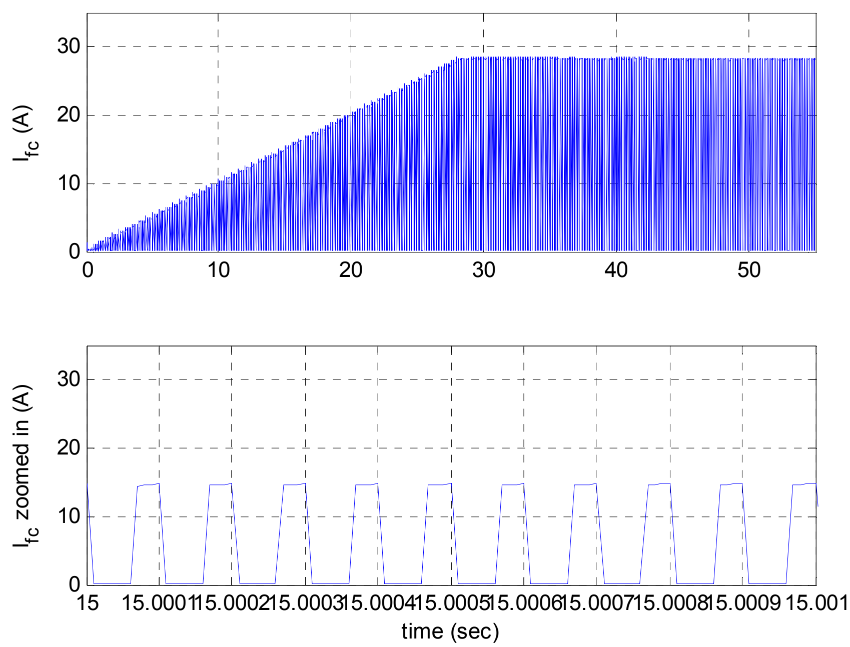

Figure 6.10: Fuel cell current #1

The load current in Figure 6.11 is much like the load power profile in Figure 6.1. The load current should follow the power demand, because the load voltage is nearly constant at 70V ± 5%.

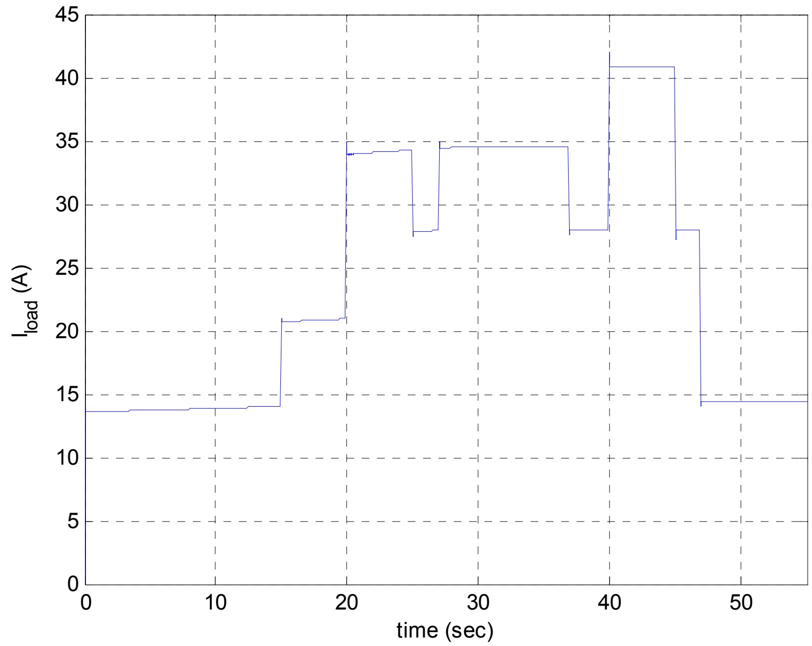

Figure 6.11: Load current #1

6.2 Simulation Results for Dynamic Load 2

Figure 6.12 shows load profile #2. The simulation for load #2 starts when the fuel cell is warmed up and at steady state. We simulated the startup routine for load profile #1, and it is unnecessary to repeat it. Load scenario profile #2 was deliberately chosen to cause the power supply's performance criterion to be violated. As a result, the controller is tested to see how well it responds to "violent" loads. The battery initial SOC was also started at 60%, so the high-level controller would have to take necessary action right away.

Load profile #2's window of power is from ~3.5kW to ~.5kW. So the fuel cell's power cannot remain at a constant 2kW, because the battery's peaking power rating is only ± 1kW. So when the load power exceeds 3kW, the fuel cell power needs to increase to avoid the battery power exceeding its rating for extended periods of time. Figure 6.13 indicates that the load voltage also goes outside of the ± 5% tolerance range.

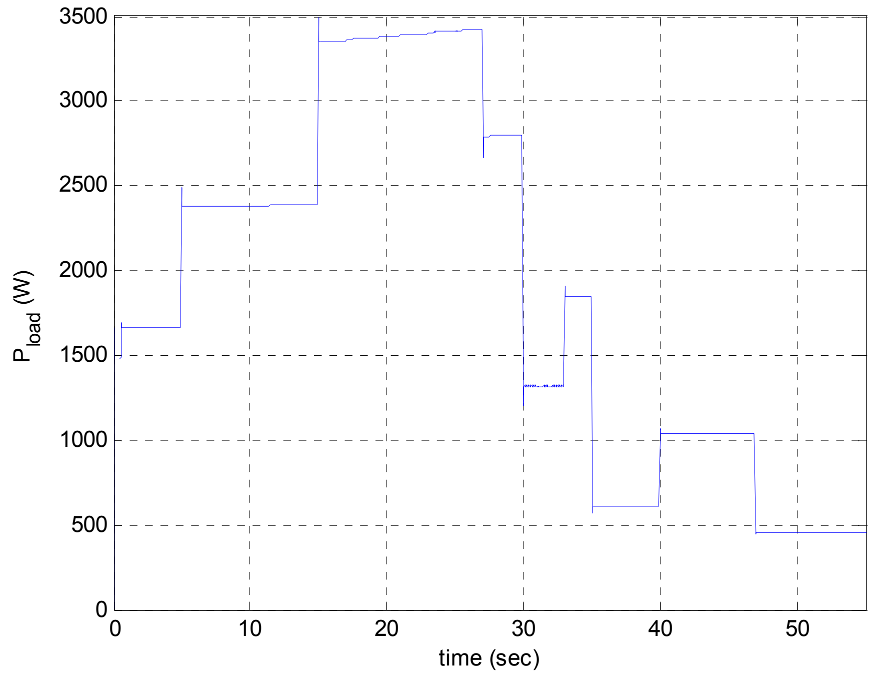

Figure 6.12: Dynamic load profile #2

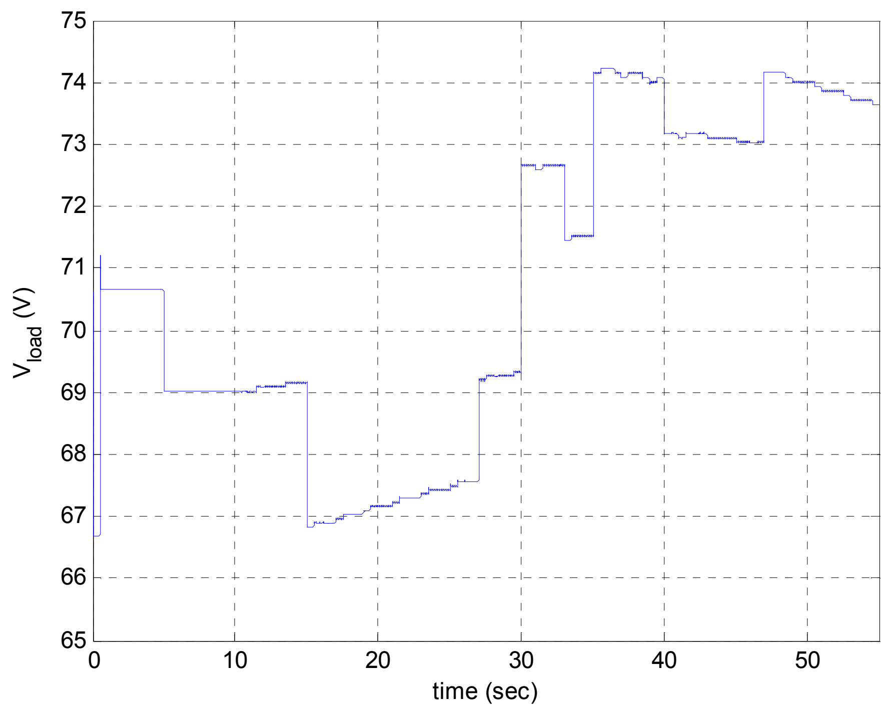

Figure 6.13: Load voltage profile #2

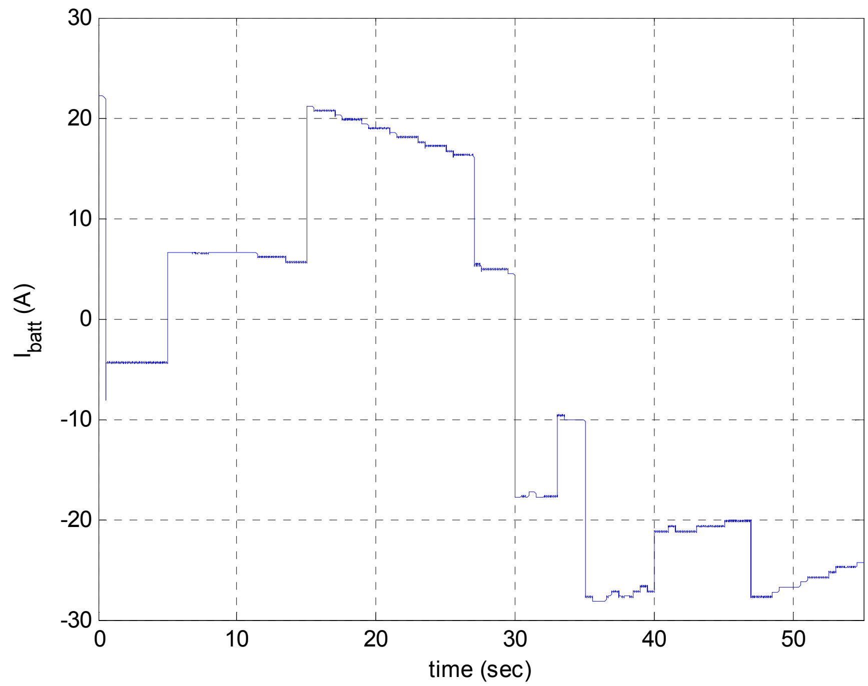

Figure 6.14: Battery current #2

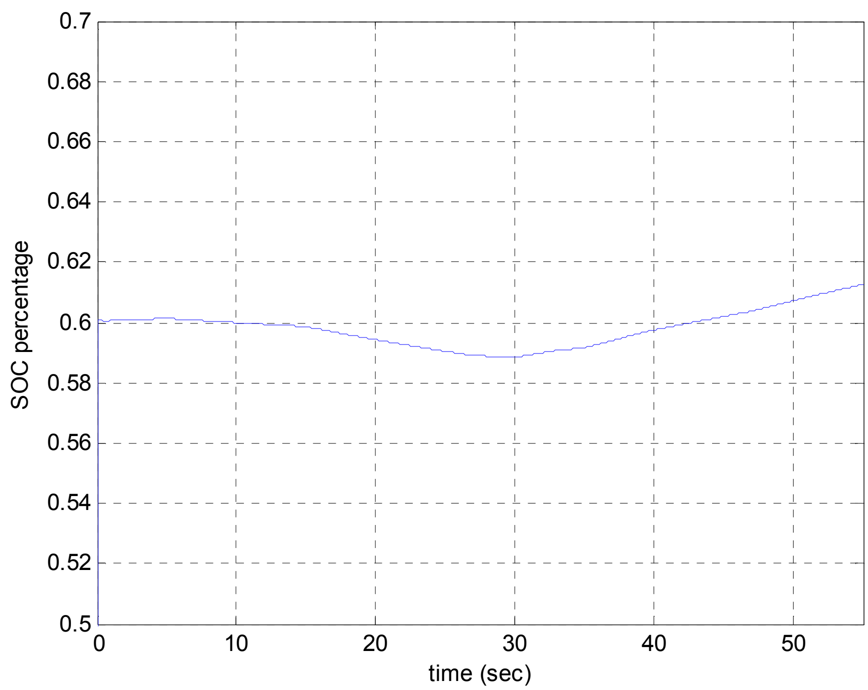

Figure 6.15: Battery SOC #2

Figure 6.14 shows that the battery current exceeds its rating of ± 15A, so that means the high-level controller would detect this phenomenon and slowly increase the fuel cell power to bring the battery current to within safe limits. You can see in Figure 6.14 where the controller is attempting to bring the battery current back down between 15 seconds and 30 seconds. Figure 6.15 also shows that the battery SOC goes below 60%, so that would also cause the high level controller to increase the fuel cell power.

Looking at Figure 6.12, you can see that the load power is too high from 15 seconds to 30 seconds. Then looking at Figure 6.16 you can see that the fuel cell relaxes the efficiency constraint to cater to the battery. The fuel cell power increases at a slow rate from 15 seconds to 30 seconds in the graph. As mentioned in previous chapters the fuel cell power cannot increase instantaneously, and that is why the high level controller adjusts the fuel cell power slowly between 15 seconds and 30 seconds. If the load were to remain at 3.5kW for an extended period of time, then the high-level controller would keep the fuel cell power operating above the optimal 2kW until the load dropped below 3kW.

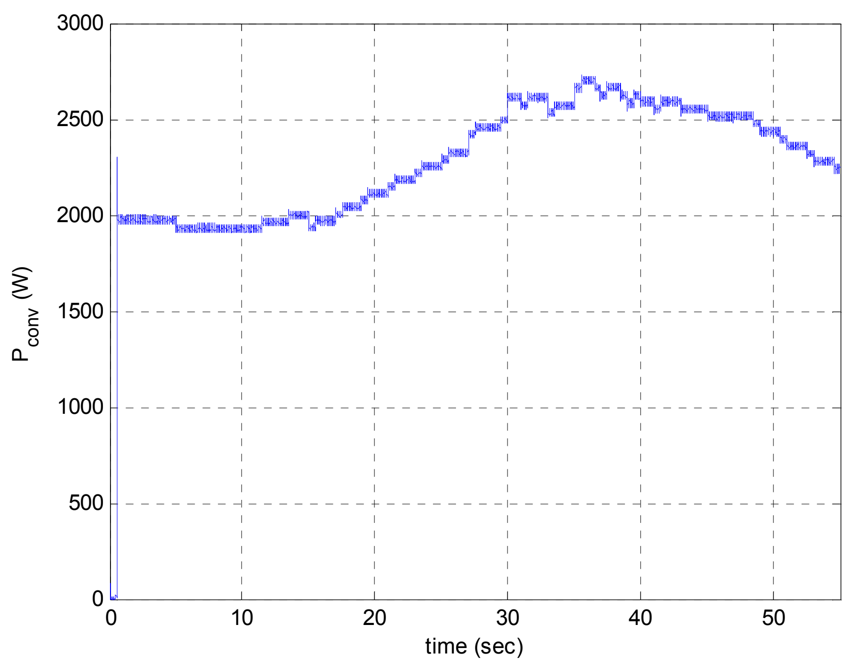

Figure 6.16: Converter output power #2

Looking back at Figure 6.12, you can see that the load power suddenly drops to about 500W at 35 seconds. This sudden drop causes the battery to be charging too much: as indicated in Figure 6.17. So after 35 seconds you can see the fuel cell power start to drop, because the high-level controller realizes that the battery charging current is too high. And Figure 6.16 reflects this slowly decreasing behavior in the fuel cell's power. The fuel cell power would eventually drop to below 2kW until the battery was charging at safe limits within -1kW. You can see in Figure 6.17 that the battery's charging power is moving in the direction of the safe limit of -1kW.

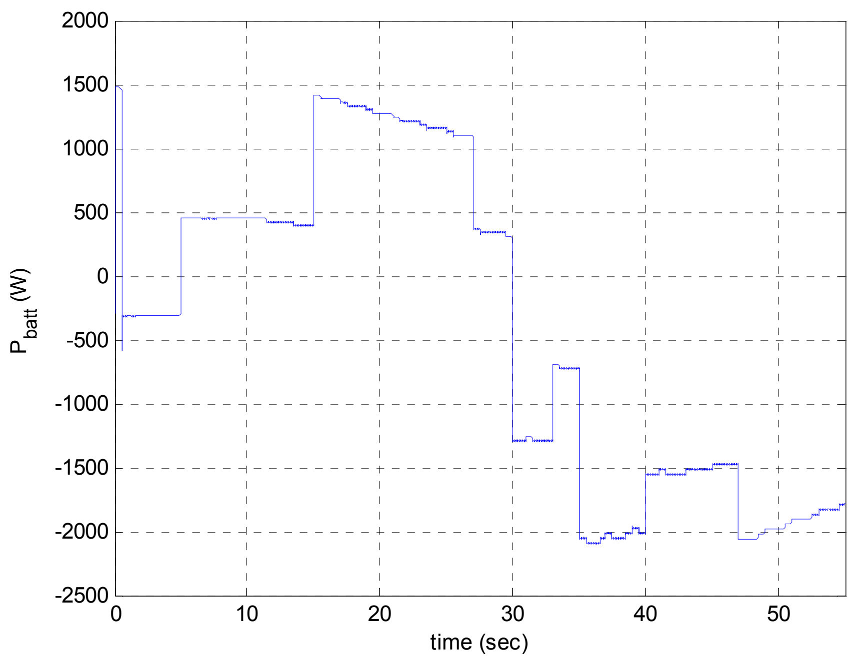

Figure 6.17: Battery power #2

Figure 6.18 shows the reference current value produced by the high level controller. It shows that the high-level controller detects when the load power is too high from 15 seconds to 30 seconds, and it shows that the high-level controller detects when the load is too low after 35 seconds. The high-level controller cannot perfectly track the load, because the fuel cell has a 30 second time constant. But the high-level controller responds as fast as the fuel cell is able. The battery power will just have to temporarily exceed its ratings when the load power makes sudden large changes above 3kW or below 1kW until the fuel cell and buck converter are able to adjust their power output.

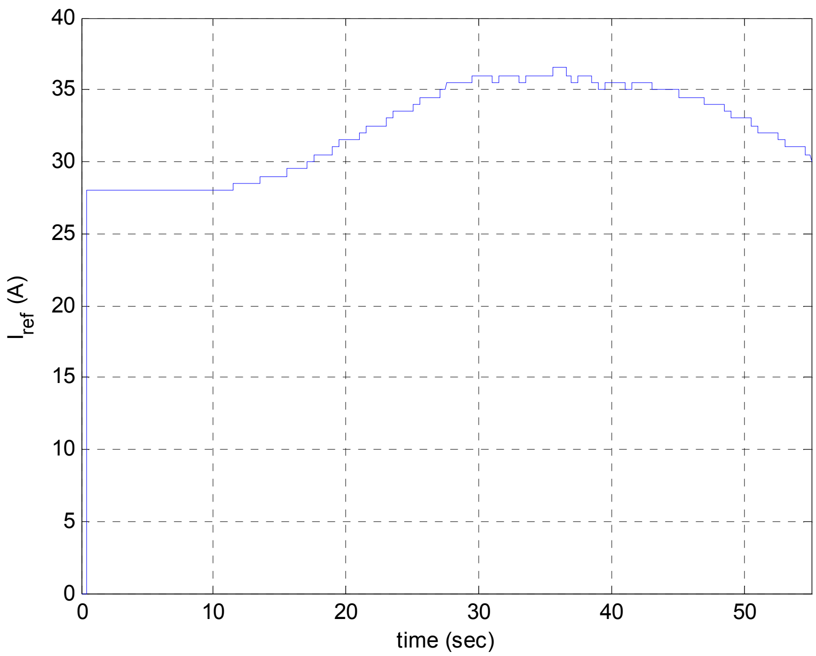

Figure 6.18: Reference current #2

Again Figure 6.19 shows how well the fuzzy logic controller tracks a reference with as little error as possible. When the reference changes the fuzzy logic controller is able to follow it with the same performance as load #1. The buck duty cycle shown in figure 6.20 converges to a steady-state value. This means the controller does not diverge and go unstable under large dynamic conditions. So that means the fuzzy logic controller is very robust.

Figure 6.21 shows the fuel cell current rise and fall when the high-level controller also causes the inductor reference current to rise and fall. This is expected, because the fuel cell's power rises and falls with the high-level controller's demand. And figure 6.22 shows the current of the load shown in figure 6.12.

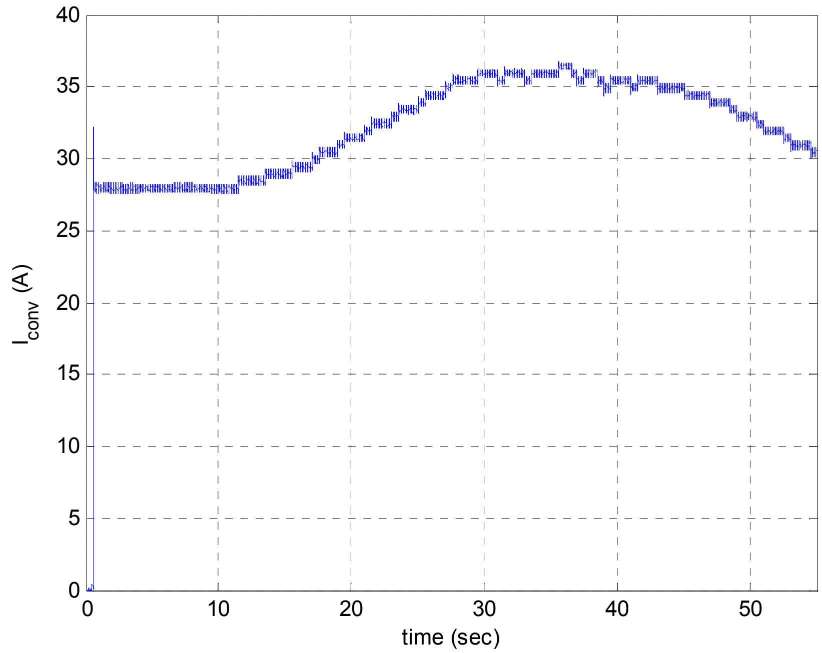

Figure 6.19: Inductor current #2

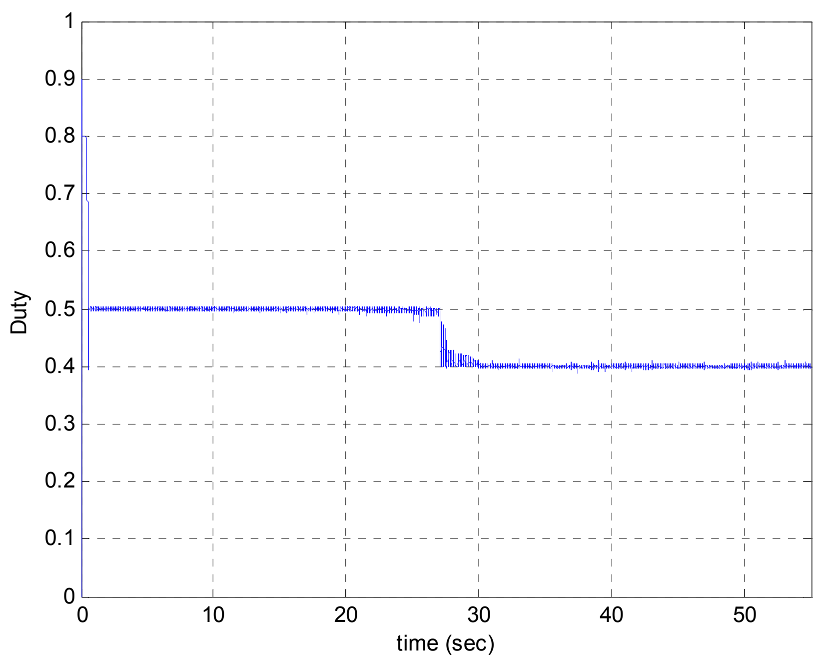

Figure 6.20: Fuzzy logic duty cycle #2

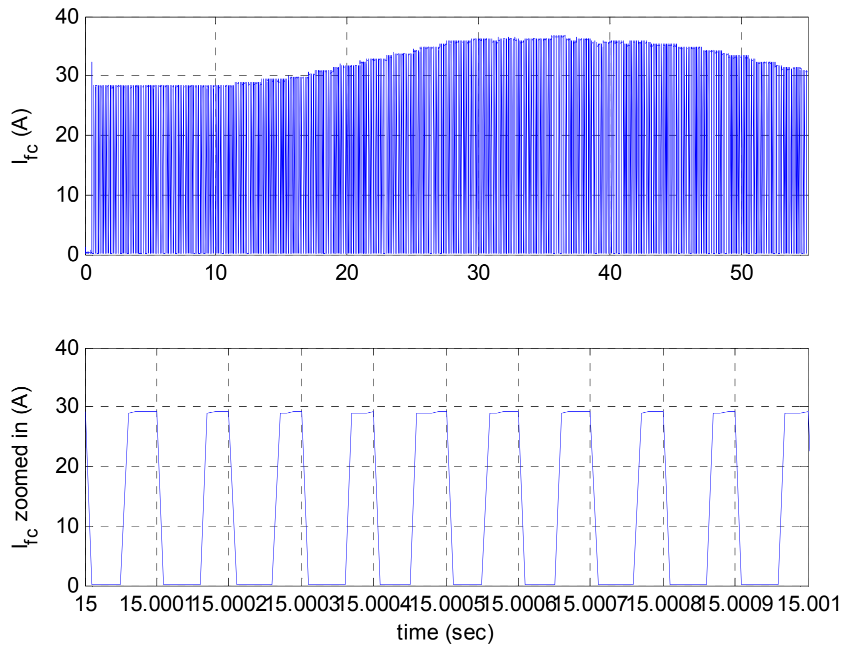

Figure 6.21: Fuel cell current #2

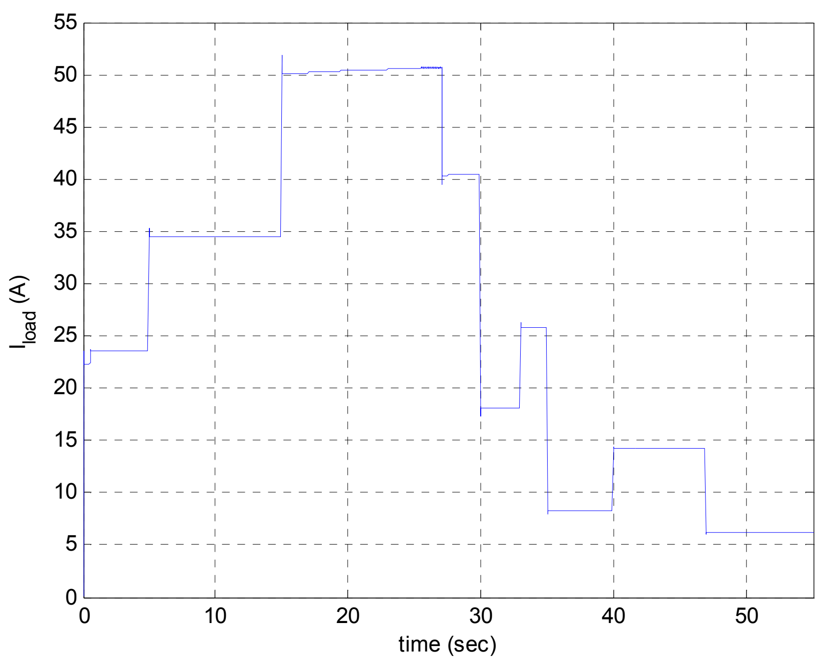

Figure 6.22: Load current #2

6.3 Assessment of Results

In conclusion the high-level controller and the fuzzy logic controller work very well. In load #1, the conditions given to the power supply are favorable to the design criteria. The load's average power was about 2kW, and the load's peaking power did not exceed ± 1kW. So under loads with these favorable conditions, the fuel cell is able to operate in its most efficient operating region the whole time.

For load #2, some of the safety criteria were violated as a result of a sudden rise and subsequent fall of power. And the load power exceeded the favorable upper limit of 3kW and lower limit of 1kW. But the high-level controller demonstrates that it is able to take appropriate actions to bring battery current, load voltage, and battery SOC back to within safe levels. But in order to take such actions the fuel cell will have to operate at power levels outside of its most efficient operating region.

CHAPTER VII
CONCLUSIONS AND FUTURE RESEARCH

In this chapter the thesis will be concluded. The advantages of the control strategy developed in this thesis will be given. Future research potential is also given.

7.1 Conclusion

This thesis investigated techniques to successfully hybridize a fuel cell and a battery, such that the advantages of each device are exploited. The fuel cell was successfully decoupled from the load dynamics, and the battery inherited all transient behavior in the dynamic load. The circuit topology using a single buck converter for the fuel cell was presented, and the simulations show that - at least in principle - one can successfully hybridize a fuel cell and a battery using this topology. The fuel cell's efficiency was and the battery's fast dynamic response time are the two most exploited advantages of each device.

It was established that in order to hybridize a fuel cell and a battery, then the converter must behave like a current source instead of a voltage source. The reason you must not use a voltage source is because the battery itself is a voltage source and you don't put two conflicting voltage sources in parallel. Also a new application of stiff systems theory was introduced in this thesis to design the buck converter.

The fuzzy logic controller designed in this thesis caused the buck converter to act as a very good current source. The high-level controller designed in this thesis was able to monitor and regulate many different variables in the power supply: namely battery SOC, battery current, and load voltage. These variables (particularly the battery) might jump to unsafe operating points as a result in a sudden drastic change in the load. But the high-level controller is able to recognize such unsafe conditions and bring the power supply's operating point back to safe levels by adjusting the output current of the buck converter.

Adjusting the buck's output current effectively adjusts the fuel cell power. So the high-level controller was able to monitor the power supply with only one degree of freedom using a multiplexing technique.

7.2 Future Research

This thesis only investigated a simulation of a hybrid power supply. Although the simulations show that the hybrid power supply and the control scheme can operate satisfactorily, a hardware prototype needs to be constructed and tested before this power supply can be made available for the public. Also coulomb counting is not a reliable method of estimating a battery's SOC. The battery's charge capacity degrades with use, so more accurate methods to estimate SOC will eventually need to be utilized.

These techniques of hybridization of a fuel cell and a battery can possibly be expanded to hybridize power sources other than batteries and fuel cells. Variations of the techniques presented in this thesis could also be employed to study the hybridization of ultra-capacitors, wind power, and solar power sources in addition to batteries and fuel cells. The untraditional technique of using a buck converter as a current source could be applied to other power supplies as well.

As briefly mentioned in Chapter III, another control strategy can be developed to cater to the battery and use it as little as possible. The objective of the control in this thesis is to have the fuel cell operate most efficiently as often as possible and conserve fuel. The controller in this thesis made no attempt to use the battery sparingly.

Since this thesis established a proof of principle that one can successfully hybridize a fuel cell and a battery using only a buck converter, many doors are now opened. Other converters can be studied, that might be more favorable than the buck converter. Regenerative loads can also be investigated.

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APPENDIX A

FUZZY LOGIC CODE

```
function Duty  = fcn(Iout, Iref, step_size)
% This block implements the fuzzy logic control algorithm
% seen in the fuzzy logic table in chapter 4

persistent last_D;
if isempty(last_D)
   last_D = .9;
end

Duty = last_D;

persistent prev_Iout;
if isempty(prev_Iout)
   prev_Iout = [0, 0];
end

prev_Iout(2) = prev_Iout(1);
prev_Iout(1) = Iout;

%%% calculate derivative of Iout
derivative = prev_Iout(1) - prev_Iout(2);

if derivative > 0
    if Iout < Iref %% error is positive
        Duty = Duty - step_size;
    else           %% error is negative
        Duty = Duty + 2*step_size;
    end
end

if derivative < 0
    if Iout < Iref %% error is positive
        Duty = Duty - 2*step_size;
    else           %% error is negative
        Duty = Duty + step_size;
    end
end

if derivative == 0
    if Iout < Iref
        Duty = Duty - step_size;
    end

    if Iout > Iref
        Duty = Duty + step_size;
    end
```

```
end

if Duty > .9
    Duty = .9;
end
if Duty < .1
    Duty = .1;
end

last_D = Duty;
```

APPENDIX B

HIGH-LEVEL CONTROLLER CODE

```
function I_ref = flowchart(Iload, Vload, Ibatt, SOC, parameters)
% This functions determines Iref based on the flowchart algorithm
% presented in chapter 4
% This function also initializes the startup routine for the fuel cell

persistent Iref;
if isempty(Iref)
   Iref = 0;
end

persistent STARTUP;
if isempty(STARTUP)
   STARTUP = 1;
end

persistent violate;
if isempty(violate)
   violate = 0;
end

persistent service %%% determines which parameter to service
if isempty(service)
   service = 1;
end

I_batt_max = parameters(1);
 I_optimal = parameters(2);
V_load_max = parameters(3);
V_load_min = parameters(4);
   SOC_min = parameters(5);
   SOC_max = parameters(6);

if (service == 1)
    violate = 0;
end

%%% Startup Routine
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(Iload > 0)
    if(STARTUP == 1)
       if(Iref < I_optimal)
          Iref = Iref + .5;
       end
       if(Iref >= I_optimal)
           STARTUP = 0;
       end
```

```
    end
end

%%% Flowchart Function
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (STARTUP == 0)                %%% service load voltage
   if (service == 1)
      if (Vload > V_load_max)
         Iref = Iref - .5;
         violate = 1;
      end
      if (Vload < V_load_min)
         Iref = Iref + .5;
         violate = 1;
      end
   end

   if (service == 2)             %%% service battery current
      if (Ibatt > I_batt_max)    %%% discharging too much
         Iref = Iref + .5;
         violate = 1;
      end
      if (Ibatt < -I_batt_max)   %%% charging too much
         Iref = Iref - .5;
         violate = 1;
      end
   end

   if (service == 3)             %%% service battery SOC
      if (SOC > SOC_max)         %%% batt too full
         Iref = Iref - .5;
         violate = 1;
      end
      if (SOC < SOC_min)         %%% batt too low
         Iref = Iref + .5;
         violate = 1;
      end
   end

   if (service == 4)             %%% service fuel cell efficiency
       if(violate == 0)
           if(Iref ~= I_optimal)
               if(Iref > I_optimal)
                   Iref = Iref - .5;
               end
               if(Iref < I_optimal)
                   Iref = Iref + .5;
               end
           end
       end
   end
```

```
%%%% Restart Service Parameter
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   service = service + 1;
   if (service == 5)
       service = 1;
   end
end

I_ref = Iref; %%% output
```

APPENDIX C

PARAMETER DEFINITIONS CODE

```
% This MATLAB program initializes constants for the
% hybrid power supply model in simulink

clear all
clc

     BUCK_L = .01;            % inductor size
     C_filt = 3.6e-3;         % filter capacitor size
     f_BUCK = 10000;          % switching frequency of the converter
     T_BUCK = 1/f_BUCK;       % switching period of the converter

%%% controller specifications
  control_f = 10000;          % fuzzy logic frequency
  control_T = 1/control_f;    % fuzzy logic sample period
  step_size = .001;           % fuzzy logic adjustment step size
       f_CC = 5*f_BUCK;       % coulomb counter frequency
       T_CC = 1/f_CC;         % coulomb counter switching period
flowchart_f = 2;              % flowchart controller frequency
flowchart_T = 1/flowchart_f;

%%% fuel cell and battery characteristics

     V_batt = 70;
     R_batt = .15;
    batt_Ah = 6.5;
 I_batt_max = 15;
   SOC_init = .75;
    SOC_max = .9;
    SOC_min = .6;
 V_load_max = V_batt*(1.05);
 V_load_min = V_batt*(.95);

      V0_FC = 200;
   R_ohm_FC = 1.41;
   R_act_FC = 1.41;
   C_act_FC = 21;
  I_optimal = 28;

batt_parameters = [ I_batt_max,  % parameters used in the flowchart
                     I_optimal,
                    V_load_max,
                    V_load_min,
                       SOC_min,
                       SOC_max, ];

%%% Dynamic load characteristics
    R_load_1 = 5;              % various load resistance values
```

```
    R_load_2 = 10;
    R_load_3 = 5;
    R_load_4 = 10;
    R_load_5 = 5;

 t_step_in_1 = 0;              % various times for the load resistances
t_step_out_1 = 100;            % to switch on or off to create
 t_step_in_2 = 15;             % dynamic load conditions
t_step_out_2 = 25;
 t_step_in_3 = 20;
t_step_out_3 = 47;
 t_step_in_4 = 27;
t_step_out_4 = 37;
 t_step_in_5 = 40;
t_step_out_5 = 45;

disp('power supply parameters set');
```

APPENDIX D

PULSE GENERATOR CODE

```
function gate  = square_gen(real_time, D, T)
% This block creates a square wave with the inputs
% duty cycle D and switching period T

time_now = mod(real_time, T);
high_time = T*D;

if high_time <= time_now
    gate = 1;
else
    gate = 0;
end
```

APPENDIX E

COULOMB COUNTER CODE

```
function SOC = counter(Ibatt, batt_Ah, SOC_init, T_samp_hold)
% This function determines the battery's state of charge
% (SOC) by sampling the current periodically and multiplying
% the sampled current by the sampling period to determine the
% change in coulombs over each sampling period.

persistent previous_SOC;
if isempty(previous_SOC)
   previous_SOC = SOC_init;
end

delta_SOC = (T_samp_hold*Ibatt)/(batt_Ah*3600);
SOC = previous_SOC + delta_SOC;
previous_SOC = SOC;
```

VITA

Richard Charles Smith earned his Bachelor of Science degree in electrical engineering from The University of Texas at Austin in May 2006. He entered the Master of Science program at Texas A&M University in August 2006 and received his MS degree in August 2009. His research interests include control systems for power electronics and alternative energy systems. His ambitions are to live and work in Texas in the energy industry. He can be reached via email at electricalsmith@gmail.com. He can also be reached through Dr. M. Ehsani, Power Electronics Laboratory, Electrical Engineering Department, Texas A&M University, College Station, Texas 77843-3128.