Energy Management System Design and Testing in a Dual-Voltage System

by

Amy W. Ng

Submitted to the Department of Electrical Engineering and Computer Science
In Partial Fulfillment of the Requirements for the Degrees of Bachelor of Science in Electrical Engineering and Computer Science and Master of Engineering in Electrical Engineering and Computer Science at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY May 17, 2001 © Massachusetts Institute of Technology 2001. All rights reserved.
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ABSTRACT

Automobile manufacturers have committed to the development of new dual-voltage electrical architectures to meet the ever-increasing demands of the automotive electrical system. The MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems has proposed a dual-voltage system consisting of a high-power alternator delivering current to a 42V bus, which is charged by a 36V battery and connected via a DC/DC converter to a 14V bus, which is charged by a 12V battery. This thesis will investigate the effects of an energy management algorithm, varying vehicle driving speeds, and load events on power flow and energy usage in the dual-voltage system, in an effort to evaluate power demands and provide insight into the specification of key power supply components such as the alternator, batteries, and DC/DC converter.

Thesis Supervisor: Prof. Bernard C. Lesieutre
Title: Associate Professor of Electrical Engineering and Computer Science
Acknowledgments

I would like to thank Professor Bernard C. Lesieutre for originally entrusting me with this project. I would also like to thank Dr. Tom Keim for his insight and help with this project. A million thanks go to my parents, to whom I am always indebted for their love, support and prayers. I am truly grateful to Sally SMN, Pastor Chris, Cindy unni, my housemates Jung Yoon unni, Anne unni, Julie, and Teresa for doing everything they could to keep me going and sane, the young adult leaders Hee Chin JDSN, Jean SMN, and Sarah unni for all their prayers and encouraging words each time they saw me, Jason for always cheering me up and listening to me when I needed to complain, Becky JDSN and Pastor Paul I know who constantly prayed for my studies and spiritual life, and the rest of my church family for their encouragement throughout college and graduate school. I would like to recognize and thank Vahe Caliskan and James Geraci for their work in simulations and breadboard respectively for my project. Finally and most importantly, all my praise and thanks go to Jesus Christ, my Savior and Lord, without whom I would not be able to live a worthy and purposeful, full and abundant life. For His grace in saving me from my sin and pursuing me to walk with Him daily, especially through my college and graduate years, to Him be all glory, honor and praise.
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Chapter 1

Introduction

1.1 Background

In anticipating requirements for more electrical features and greater efficiency from the next generation of automobiles, the automotive industry has almost universally begun to examine the efficacy of 42V automotive electrical systems. This is motivated in part by the appearance of new electrical loads for emission control, safety, and passenger comfort, which will create a much greater demand for electrical power than can be efficiently supplied by today's 14V electrical system. In addition, improving technology will allow many existing mechanical loads to be made electrical, in order to improve efficiency. Electromechanical valve engines, for example, are likely to be introduced within the next couple of years. Furthermore, future cars may include “an electrically heated windshield, electric water pump, electric engine-cooling fan, electric steering and possibly an electric-pump-driven active suspension system” [5]. Consequently, future cars will not only have a greater number of loads, but also additional loads will require significantly more electrical power than existing loads. A higher voltage electrical system also facilitates gains in fuel economy by allowing devices currently driven directly by the engine, such as engine valves and cooling fans, to be driven electrically. [1 - 2]

Not all electrical loads stand to benefit from operating at an increased voltage. Some loads, such as filament-based incandescent lights, experience decreased lifetimes as voltage increases. Electronic control units (ECUs), used for applications such as engine control, traction control, and climate control, also prefer to operate at lower voltages. This is because ECUs depend on linear regulators to convert the 14V-bus voltage to the 5V used by each ECU’s internal circuitry. The efficiency of such regulators decreases as the input voltage increases, so an increased bus voltage increases the power consumption of the ECU [3]. Therefore, the need exists to allow certain high-power loads to realize advantages of higher-voltage operation, while simultaneously allowing low-power loads to
operate at their present 14V level. This need is addressed by the study of dual-voltage generation systems that power both 42V and 14V loads simultaneously.

1.2 Motivation

The MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems (See Section 1.3.1) thus proposed a dual-voltage system because of the foreseeable need for a new, more powerful automotive electrical system while retaining the conventional voltage. This dual-voltage system consists of the familiar 14V bus along with an additional 42V bus. Forty-two volts was chosen as the nominal voltage of the additional bus because of a number of factors, including safety specifications and affordable semiconductor device voltage limitations [5]. In the proposed dual-voltage system, high-power demanding loads, such as the starter and heaters, are placed on the 42V bus, while smaller loads, such as driver electronics, are placed on the 14V bus. An alternator supplies current directly to the 42V bus, which is also connected to a 36V battery. A 12V battery and a DC/DC converter that is connected to the 42V bus supply the 14V bus.

If size, weight, and money were not an issue, the alternator that supplies current directly to the 42V bus and indirectly to the 14V bus via a DC/DC converter should be designed to provide enough power so no possible combination of loads which could drain the batteries. Because of physical and economic limitations, however, such an alternator is not obtainable. Furthermore, such an alternator might not be the most desirable alternative. Due to the start and stop nature of automobile driving, there are times when the car batteries are being drained and times when they are being charged. The important thing is that the change in the state of charge of each battery over the complete drive cycle is zero or positive. If it were possible to intelligently control the flow of charge between the two batteries so that no net charge is lost by either battery over a given drive cycle, it would be possible to specify an alternator that would not have to provide enough power to keep both batteries fully charged at all times. This method of intelligently controlling the flow of energy throughout the automobile is called energy management. Such an
energy management system would allow the use of a smaller alternator and therefore reduce the weight and cost of the automobile.

1.3 Project Overview

1.3.1 The MIT/Industry Consortium

This project was developed as a part of the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, a research group within the Laboratory for Electromagnetic and Electronic Systems (LEES) at MIT. The work conducted by the Consortium is divided into the research units listed below in Table 1.

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<th>Research Unit Number</th>
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<th>Description</th>
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<td>DC/DC Converters for Dual-Voltage Electrical Systems</td>
<td>Investigate the design of dc/dc converters for dual-voltage systems and develop fundamental technologies, which facilitate their use in this application.</td>
</tr>
<tr>
<td>2a</td>
<td>High-Power Combined Starter/Alternator Machine</td>
<td>Investigate the design and cost-optimization of a direct-drive high-power combined starter/alternator using an interior permanent-magnet (IPM) synchronous machine.</td>
</tr>
<tr>
<td>2b</td>
<td>High-Power Generation</td>
<td>Investigate the design and cost optimization of an inductor alternator for use as a high-speed high-power automotive power source.</td>
</tr>
<tr>
<td>2c</td>
<td>Starter/Alternator Control System</td>
<td>Design, build, and test a digital control system capable of robustly controlling the combined starter/alternator IPM machine drive, selected for study by Research Unit 2A, over its complete range of starting and generating conditions.</td>
</tr>
<tr>
<td>2d</td>
<td>Electronically-Aided Power Generation and Control</td>
<td>Investigate the design and control of high-power alternators incorporating power electronic controls.</td>
</tr>
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<td>3</td>
<td>MAESTrO 3.5 Development</td>
<td>Develop a knowledge based software tool for the design, analysis, and evaluation of automotive electrical systems Project completed in June 1998</td>
</tr>
<tr>
<td>4</td>
<td>Electrical System Transient Investigation</td>
<td>Investigate the generation and control of high-power electrical transients in dual/higher-voltage power supply architectures Project merged with Research Unit 5.1 in June 2000</td>
</tr>
<tr>
<td>5</td>
<td>Comparative Power Supply Architecture Evaluation</td>
<td>Develop comparative evaluations of candidate dual/higher-voltage power supply architectures to provide insight into their desirability for different vehicle applications. Project merged with Research Unit 5.1 in June 2000</td>
</tr>
<tr>
<td>5.1</td>
<td>Power Supply Architecture Transients/Performance</td>
<td>Evaluate the electrical performance, including transients of candidate dual/higher voltage power supply architectures.</td>
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<td>6</td>
<td>Load-Flow Study of the Dual-Voltage System</td>
<td>Evaluate power and energy flow in dual-voltage electrical systems during vehicle drive cycles in order to provide insights into the sizing of key power supply components. Project merged with Research Unit 6.1 in September 1999.</td>
</tr>
<tr>
<td>6.1</td>
<td>Energy Management System Design and Testing in a Dual-Voltage System</td>
<td>To control energy flow and storage in a dual-voltage automobile electrical system.</td>
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<td>7a</td>
<td>Dual-Voltage System Protection and Fusing</td>
<td>Investigate alternative strategies, configurations, and components to provide fault protection in dual-voltage systems. Project completed in June 1999.</td>
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<td>7b</td>
<td>Investigation of Electric Arcs in 42 Volt Systems</td>
<td>Investigate quantitative differences in electric arcs at 42V and 14V including periodic recurring arcs and opening of connectors under load.</td>
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<td>9</td>
<td>EMI/EMC in Dual-Voltage Electrical Systems</td>
<td>Investigate EMI/EMC issues and suppression techniques associated with the vehicle introduction of higher voltages and increased accessory power levels.</td>
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<td>10</td>
<td>Economic Analysis of 42V PowerNet Automobile Electrical Systems</td>
<td>Understand economic implications of various automobile electrical systems architectures and component designs to help identify possible transition strategies from existing automobile electrical system to one or more alternative systems.</td>
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<tr>
<td>11</td>
<td>Non-Conventional Electricity Sources for Motor Vehicles</td>
<td>Explore alternatives to the engine-driven generator for automotive use.</td>
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Table 1: Research Units of the MIT/Industry Consortium

The work described in this paper was conducted under Research Unit #6.1, Energy Management System Design and Testing in a Dual-Voltage System. The work in this research unit is the combined continuation of the work in Research Unit #6, The Load-Flow Study of the Dual-Voltage System, and Research Unit #8, 42V PowerNet System Management Using Multiplexed Remote Switching. Research also include collaborative efforts with Research Units #1, and #4 as will be described throughout this thesis.
1.3.2 Goals of the Project

As summarized in Table 1, the research presented in this paper seeks to design and test an energy management system in a dual-voltage environment. Through software simulations and hardware testing, combined with knowledge of previous research unit results, more insights will be developed for battery and alternator specification.

The goal of this project is to use the existing dual voltage design, incorporate a sophisticated energy management system based on a state of charge algorithm into the design, simulate, test, and gain new insights in the dual voltage DC/DC converter architecture. New models for the batteries and DC/DC converter are developed for long-term simulations with the proposed energy management algorithm. Then simulations performed with Saber, a circuit simulating software tool, using drive cycles and load cycles that were used for previous simulations. A hardware version of the energy management system in a dual-voltage system is implemented on a MIT breadboard facility. All results are compared with past results from Research Units #6 and #8 to develop new insights into the energy management algorithm and system discussed in this thesis.

A new load-matching technique is introduced that allows substantial increases in the output power capability and efficiency of automotive alternators. Analysis and implementation of this new alternator is also done using Saber. Although the model will not be implemented in the energy management system in this thesis, it is hoped that it can be incorporated in the future to further benefit the energy management efficiency of a dual-voltage system.

1.3.3 Overview of Research Methods

The dual-voltage architecture of Research Unit #6 and an energy management algorithm of Research Unit #8 are used in this thesis. Detailed explanations of these two key elements are discussed in sections 2.1 The Dual-Voltage Architecture and 2.2 The Energy Management Algorithm. Insights into key power supply components were developed through software simulations and hardware testing of the energy management in the dual-voltage system.
For software simulations, the circuit simulation tool Saber was used. Saber has a graphical user interface with which one can model the circuit being simulated. Using MAST, the Saber programming language, Saber models were developed for the batteries and the DC/DC converter in order to implement the energy management algorithm. By connecting the components developed under Research Unit #6 and the energy management components as specified in the dual-voltage architecture, a complete design of the new energy management system in the dual-voltage system was made. A DC analysis is run to find the DC operating point of the system, followed by a transient analysis. By simulating the system over time, the flow of power through the system was monitored as the power supply and demand changed with vehicle speed and load on-off transitions. The simulation results, and in particular, the final battery states of charge at the end of each transient analysis, were then used to make judgments regarding the power supply components.

For hardware testing, the MIT breadboard facility developed under Research Unit #8 was used. Using LabView 5.0 and the C programming language, the energy management system was incorporated into the breadboard facility. Some modification and debugging was necessary for the full dual-voltage system with new energy management to function properly, but the hardware components developed under Research Unit #8 were adequate for a complete design. The breadboard facility has a graphical user interface with which one can input drive and load cycles, turn on and off loads, and run the tests. Physical tests were run with the implemented energy management algorithm under varying driving and loading situations. Tests were run under conditions similar to the software simulation conditions; the flow of power through the system was monitored as the power supply and demand changed with vehicle speed changes and load on-off transitions. The test results, and in particular, the real-time battery currents and voltages, were then used to make judgments regarding the power supply components.

The breadboard facility tests confirmed the results from Saber simulations. Not only did they confirm simulation results; it also supports the use of the state of charge energy management algorithm in an energy management system. The tests also verify that the dual-voltage system indeed benefits from an energy management system.
Chapter 2

Overall Design

2.1 The Dual-Voltage Architecture

The dual-voltage power supply architecture under consideration by this thesis is pictured in Figure 1.

![DC/DC Converter Dual-Voltage Architecture](image)

**Figure 1: DC/DC Converter Dual-Voltage Architecture**

The DC/DC converter architecture is the least intrusive to the alternator, since the converter is simply connected to the DC rectifier output of a 42V alternator. In this configuration the converter functions as a buck converter to step the 42V generated by the alternator down to 14V for the low voltage bus. The majority of dual-voltage power supply development for automotive applications has focused around the DC/DC converter. However, the DC/DC converter is a potentially costly addition to the automobile because it requires relatively high-cost active and passive components, as well as large input and output filters [4]. However, unlike the DC/DC converter, far less is known about the ability of dual-voltage alternators or any other methods to generate
power for automotive electrical systems in a cost-effective manner and with as little added
weight as possible. This is because few, if any, such alternate components have been
produced and tested within an automobile. Therefore, this thesis will set out to examine
only the DC/DC converter dual-voltage architecture using circuit simulation and hardware
testing.

The basic dual-voltage design consists of two buses; one connected to the existing
standard 12V battery and regulated at 14V, and the other connected to a 36V battery and
regulated at 42V. The higher voltage bus is connected directly to the output of the 42V
alternator. All high power loads are located on the 42V bus. The 14V bus is connected
to the higher bus via a DC/DC converter. All low power loads are placed on the 14V bus.

2.2 The Energy Management Algorithm

Energy management algorithms are not new to the automobile industry. Today’s
automobile employs a simple yet effective energy management algorithm. It uses a
temperature compensated voltage sensor to measure the battery’s voltage and uses this
information to control the excitation of the alternator field winding, and thus the amount
of power that the alternator will deliver to the system.

The 42V/14V electrical system will also employ an energy management algorithm;
however, the additional batteries make the control of the system more complex, and the
possible benefits of having a good energy management algorithm greater.

Previous work in both Research Units #6 and #8 employed bus voltage regulation,
which is the 42V/14V extension of today's energy management algorithm. It employs a
temperature compensated voltage sensor on the outputs of the DC/DC converter and the
42V alternator to measure the voltage on each bus and then uses typical voltage-time
discharge curves of lead acid batteries to infer the state of charge of each battery. It has
the advantage that it can be easily implemented and can be expected to maintain battery
charge for both batteries about as well as today’s highly satisfactory system.

Due to the dual bus and dual battery nature of the DC/DC converter architecture, a
more sophisticated energy management algorithm is needed to fully determine the
architecture's overall electrical performance characteristics, and to quantify the relative
characteristics and power demands required to achieve certain minimum performance levels. Especially under city driving conditions, it is difficult, if not impossible, to evaluate the capabilities of the dual-voltage system [5]. The bus voltage regulation method to control current through the DC/DC converter in the previous dual-voltage design developed under Research Unit #6 and #8 is to set the maximum amount of current allowable to a fixed value. Though this method might be acceptable for the steady-state simulations of idle and country driving, it does not adequately respond to the dynamics of the stop-and-go city driving.

The present system of observing the bus voltage and then modifying the alternator excitation accordingly is simply trying to use the voltage information to make a guess at how much charge has been removed from the battery during a drive cycle. This algorithm does not compute a number for the state of charge which is a term often used to refer to the amount of work that the battery can do given an instantaneous set of environmental parameters. It simply reacts to the voltage.

A more sophisticated energy management algorithm employs a more complex battery model than the previous bus voltage regulation algorithm. One way to use state of charge information to help develop an energy management algorithm is to first break each battery's state of charge into a number of different regions and then make decisions based on which region each battery is in at any given time. For the purpose of this thesis, the following divisions were created:

- **Region 1:** Dangerous Overcharge \( 115\% < \text{SOC} \)
- **Region 2:** Acceptable Overcharge \( 105\% < \text{SOC} < 115\% \)
- **Region 3:** Ideal Operation \( 90\% < \text{SOC} < 105\% \)
- **Region 4:** Moderate Undercharge \( 50\% < \text{SOC} < 90\% \)
- **Region 5:** Dire Undercharge \( \text{SOC} < 50\% \)

Figure 2 shows the 5x5 decision matrix, which graphically displays part of the many different possible regions and the actions that should be taken in each [6].
This algorithm can limit the amount of current delivered by the DC/DC converter so that it is possible to charge the 12V battery at a rate that is less than the converter's maximum current delivery capability. With reduced output, the current drawn from the 42V bus by the converter is reduced. This current can instead go to the 36V battery thus reducing its rate of discharge and possibly even allow it to charge. Therefore, the situation could exist where both batteries are charging instead of, in the voltage regulation case, where only one battery is charging rapidly and the other is draining because it is feeding the charging battery.
Chapter 3

Simulating the System in Software

Simulation of the dual-voltage system required the development of a number of Saber models, including models of the alternator, the DC/DC converter, the lead-acid batteries, and the loads. Figure 3 shows the dual-voltage design without the selected energy management algorithm as it appears in Saber.

![Figure 3: The Dual-Voltage Architecture in Saber](image)

The models were all developed under Research Unit #6 and most of them are used in this thesis and will be discussed individually in the following sections. More detailed descriptions can be found in *A Methodology for Sizing Components in a Dual-Voltage Automotive Electrical System* by Irene Y. Kuo [5]
3.1 The Loads

The vehicle load list lists all electrical loads on a car, including each load’s nominal power consumption. Typical power consumption during idling and high-speed driving is also specified if those values are different from the nominal values. The load list used for this study includes future loads and specifies to which bus each load should be designated under the dual-voltage system. Loads are divided according to their nominal power consumption, high-power loads are placed on the 42V bus, and low-power loads are situated on the 42V bus. Appendix B includes two tables, one listing all 42V loads in the Saber design, and the other all 14V loads.

The power consumption of each load can be modeled in several ways. All loads are assumed to have a constant consumption method, and for the duration of the simulation, the method by which a particular load draws current stays the same. The amount of current drawn under a given power consumption method, however, might change if, for example, the load is speed-dependent; the faster the vehicle drives, the more power a speed-dependent load demands.

Three possible methods of power consumption were used: constant resistance, constant current, and constant power. Lamps and other loads whose power might fluctuate with the bus voltage were modeled as constant resistance loads. Logic and computer-type loads, such as the navigation aid, are likely to be connected to the bus through linear regulators, and thus were modeled as constant current loads. Motors, such as the starter, were approximated as constant power consumers.

In addition, some loads, such as the front windshield wipers and the heaters, have multiple settings and cannot be modeled simply by their nominal power consumption. For such loads, the Saber model accounted for three settings: low, medium, and high.
3.2 The Alternator

An alternator regulated at a specific voltage can be characterized by the amount of current it can produce at specific alternator shaft speeds: the maximum amount of current they are capable of producing at idling alternator shaft speed (1800 rpm) and high alternator shaft speed (6000 rpm). For example, a 14V 60-120A alternator may have the characteristic curve shown in Figure 4.

![Figure 4: Characteristic Curve of a 14V 60-120A Alternator](image)

The Saber alternator model used in the dual-voltage design was developed under Research Unit #4, Electrical System Transient Investigation. It is an averaged model, suitable for simulation on the order of minutes and hours. For a detailed description of the alternator, please see *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [5].
The alternator model requires the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Constant</td>
</tr>
<tr>
<td>Rs</td>
<td>Stator Resistance</td>
</tr>
<tr>
<td>Ls</td>
<td>Stator Inductance</td>
</tr>
<tr>
<td>Rf</td>
<td>Field Resistance</td>
</tr>
<tr>
<td>Lf</td>
<td>Field Inductance</td>
</tr>
<tr>
<td>p</td>
<td>Number of Pole Pairs</td>
</tr>
<tr>
<td>kp</td>
<td>Alternator Regulator Proportional Gain</td>
</tr>
<tr>
<td>Vd</td>
<td>Diode Drop in Rectifier</td>
</tr>
<tr>
<td>Rref</td>
<td>Alternator Reference Voltage</td>
</tr>
<tr>
<td>Vreg,min</td>
<td>Minimum Value of Regulation Voltage</td>
</tr>
</tbody>
</table>

Table 2: Parameters Used in Alternator Model

From the information provided in *Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models* [4], a simplified diagram of the alternator can be drawn, as seen in Figure 5.

![Figure 5: Simplified Diagram of the Averaged Alternator Model](image)
Using the diagram in Figure 5 an equation expressing the alternator output current, \( I_{\text{alt}} \), as a function of the alternator shaftspeed, \( n \), can be written:

\[
I_{\text{alt}} = \frac{kn_0 f_{\text{max}} - (V_s + 2V_d)}{\sqrt{R_s^2 + \left(\frac{\pi}{30} L_s n_p\right)^2}} - I_{f,\text{max}}
\]

**Equation A: \( I_{\text{alt}} \) As a Function of Alternator Shaftspeed**

Available data from which an alternator’s characteristic curve can be drawn specify \( I_{\text{alt}} \) for various values of \( n \). All other variables in Equation have known values except \( k \), \( R_s \), and \( L_s \). Thus, for a given alternator size, these three variable values need to be specified in order to model that particular size alternator with the Saber model.

In order to solve for \( k \), \( R_s \), and \( L_s \), Maple, a mathematics application, and the alternator data were used. For each alternator, \( I_{\text{alt}} \) was specified at 100 rpm intervals. Taking three points on the curve given by the data, three independent equations could be written of the form:

\[
\left(I_{\text{alt},0} + I_{f,\text{max}}\right)\sqrt{R_s^2 + \left(\frac{\pi}{30} L_s n_0 p\right)^2} = kn_0 f_{\text{max}} - (V_s - 2V_d)
\]

\[
\left(I_{\text{alt},1} + I_{f,\text{max}}\right)\sqrt{R_s^2 + \left(\frac{\pi}{30} L_s n_1 p\right)^2} = kn_1 f_{\text{max}} - (V_s - 2V_d)
\]

\[
\left(I_{\text{alt},2} + I_{f,\text{max}}\right)\sqrt{R_s^2 + \left(\frac{\pi}{30} L_s n_2 p\right)^2} = kn_2 f_{\text{max}} - (V_s - 2V_d)
\]

**Equation B: The 3 Equations to Solve for Parameters**

Using Maple, these three equations can be solved for the three unknowns, \( k \), \( R_s \), and \( L_s \). In order to change the type of alternator the simulation is using, the alternator parameters \( k \), \( R_s \), \( L_s \), and \( R_f \) are varied. Table 3 lists the 42V alternator parameters found using Maple. The data are derived from existing 14V alternators, as explained in
Modeling and Simulation of a Claw-Pole Alternator: Detailed and Averaged Models [5].

More significant digits are required for the parameters for accurate simulations and can be found in the same reference.

<table>
<thead>
<tr>
<th>Amps at Idle rpm (1800rpm)</th>
<th>Amps at High rpm (6000rpm)</th>
<th>k</th>
<th>( R_s (\Omega) )</th>
<th>( L_s (H) )</th>
<th>( R_f (\Omega) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>29</td>
<td>0.005258</td>
<td>0.9191</td>
<td>0.002090</td>
<td>3.44</td>
</tr>
<tr>
<td>20</td>
<td>43</td>
<td>0.004903</td>
<td>0.8011</td>
<td>0.001524</td>
<td>3.44</td>
</tr>
<tr>
<td>26</td>
<td>53</td>
<td>0.004337</td>
<td>0.1490</td>
<td>0.001060</td>
<td>3.44</td>
</tr>
<tr>
<td>31</td>
<td>61.5</td>
<td>0.012065</td>
<td>0.0612</td>
<td>0.000916</td>
<td>10.81</td>
</tr>
<tr>
<td>34</td>
<td>68</td>
<td>0.004279</td>
<td>0.2064</td>
<td>0.000853</td>
<td>3.44</td>
</tr>
<tr>
<td>40</td>
<td>77</td>
<td>0.004139</td>
<td>0.1408</td>
<td>0.000737</td>
<td>3.44</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>0.012704</td>
<td>0.2830</td>
<td>0.000637</td>
<td>11.11</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>0.004107</td>
<td>0.2719</td>
<td>0.000575</td>
<td>3.44</td>
</tr>
<tr>
<td>54</td>
<td>108</td>
<td>0.004072</td>
<td>0.2499</td>
<td>0.000531</td>
<td>3.44</td>
</tr>
<tr>
<td>60</td>
<td>120</td>
<td>0.004028</td>
<td>0.2229</td>
<td>0.000477</td>
<td>3.44</td>
</tr>
</tbody>
</table>

Table 3: 42V Alternator Parameters Obtained from Maple

So to change an alternator, the operator must input the corresponding \( k \), \( R_s \), \( L_s \), and \( R_f \) into Saber. For example, for a 60-120 alternator, they are 0.004028, 0.2229, 0.0004771, and 3.44 respectively.

### 3.3 Modeling the Lead-Acid Battery

The models for the lead-acid batteries and the DC/DC Converter needed to be developed in order to implement the state of charge energy management algorithm will be described in detail.

#### 3.3.1 Verifying Current Lead-Acid Battery Model

In the absence of any reliable software lead-acid battery models, the simulations used in the past used a beta version of a lead-acid battery model (Saber component batt_pb_1) provided by Saber version 4.7. The actual form of the battery model is encrypted by Saber. For research the preference is that a battery model can be explained and modified if need be. Investigations into the possibility of creating a new lead-acid
battery model using Saber was conducted but it was concluded that creating a new model is beyond the scope of this research. For the purposes of this study, the most important aspects of the battery model are its state of charge measurements and the manner by which it discharges. The discharging of the battery has been studied, and appears acceptable by current study and also previous conclusions from Research Unit #6.

More recently, Saber has released a new version of its software, version 5.1, which has a completely different lead-acid battery model that is again encrypted. Not only is it encrypted, the lead-acid battery model in Saber version 5.1 does not provide measurements in terms of state of charge like the previous model, but in terms of specific gravity. In order to compare past results with current work, the two versions must be compared in performance. Thus state of charge and specific gravity were thoroughly examined and properly related.

First, a simple test was done in order to prove that the old battery model functioned similarly to the new battery model. Each battery model was connected to a variable source and the same varying source waveform was imposed. The current and voltage curves are shown in Figure 6 and Figure 7.
Figure 6: Current Curves for Old (top) and New (bottom) Saber Battery Models

Figure 7: Voltage Curves for Old (top) and New (bottom) Saber Battery Models
Since the curves resulted are similar, one can conclude that indeed the two battery models function the same. Therefore, the new version 5.1 battery model, like the old version 4.7 model, can be accepted and used in simulations from here on.

In order to properly relate the new lead acid battery model’s specific gravity output to the old battery model’s state of charge output, simulations done previously using the old model were repeated with the exchange for the new battery model. In particular, 23 different simulations were conducted at idle conditions (see section 4.2.1 Idle Parameters) and the specific gravity recorded.

Table 4 shows the list of simulations done to test and relate the new battery model to the old battery model.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>100</td>
<td>8.5</td>
<td>0.738</td>
<td>0.703</td>
<td>1.1959</td>
<td>1.1862</td>
</tr>
<tr>
<td>15</td>
<td>85</td>
<td>8.25</td>
<td>0.688</td>
<td>0.654</td>
<td>1.1825</td>
<td>1.1729</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>7.75</td>
<td>0.61</td>
<td>0.59</td>
<td>1.1619</td>
<td>1.1546</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
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<td>1.1114</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>10</td>
<td>0.78</td>
<td>0.79</td>
<td>1.2033</td>
<td>1.2064</td>
</tr>
<tr>
<td>20</td>
<td>85</td>
<td>10</td>
<td>0.726</td>
<td>0.741</td>
<td>1.1926</td>
<td>1.1961</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>10</td>
<td>0.67</td>
<td>0.68</td>
<td>1.1776</td>
<td>1.1812</td>
</tr>
<tr>
<td>26</td>
<td>100</td>
<td>15</td>
<td>0.86</td>
<td>0.89</td>
<td>1.2279</td>
<td>1.2355</td>
</tr>
<tr>
<td>26</td>
<td>85</td>
<td>16</td>
<td>0.855</td>
<td>0.86</td>
<td>1.2273</td>
<td>1.2279</td>
</tr>
<tr>
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<td>70</td>
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<td>0.8</td>
<td>0.84</td>
<td>1.2125</td>
<td>1.2227</td>
</tr>
<tr>
<td>26</td>
<td>30</td>
<td>16</td>
<td>0.6</td>
<td>0.6</td>
<td>1.1626</td>
<td>1.1568</td>
</tr>
<tr>
<td>31</td>
<td>100</td>
<td>20</td>
<td>0.95</td>
<td>0.93</td>
<td>1.2526</td>
<td>1.2464</td>
</tr>
<tr>
<td>31</td>
<td>85</td>
<td>20</td>
<td>0.942</td>
<td>0.92</td>
<td>1.2505</td>
<td>1.2431</td>
</tr>
<tr>
<td>31</td>
<td>70</td>
<td>20</td>
<td>0.93</td>
<td>0.91</td>
<td>1.2475</td>
<td>1.2382</td>
</tr>
<tr>
<td>31</td>
<td>50</td>
<td>20</td>
<td>0.9</td>
<td>0.87</td>
<td>1.2408</td>
<td>1.2272</td>
</tr>
<tr>
<td>31</td>
<td>30</td>
<td>19</td>
<td>0.78</td>
<td>0.81</td>
<td>1.2099</td>
<td>1.2078</td>
</tr>
<tr>
<td>31</td>
<td>15</td>
<td>19</td>
<td>0.584</td>
<td>0.595</td>
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<td>1.1428</td>
</tr>
<tr>
<td>34</td>
<td>100</td>
<td>21.5</td>
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<td>0.99</td>
<td>1.26</td>
<td>1.2666</td>
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<tr>
<td>34</td>
<td>85</td>
<td>21.5</td>
<td>0.976</td>
<td>0.986</td>
<td>1.2591</td>
<td>1.2666</td>
</tr>
<tr>
<td>34</td>
<td>70</td>
<td>21.5</td>
<td>0.971</td>
<td>0.982</td>
<td>1.2579</td>
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</tr>
<tr>
<td>34</td>
<td>50</td>
<td>21.5</td>
<td>0.96</td>
<td>0.97</td>
<td>1.2553</td>
<td>1.2665</td>
</tr>
<tr>
<td>34</td>
<td>30</td>
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<td>0.95</td>
<td>0.94</td>
<td>1.254</td>
<td>1.2665</td>
</tr>
<tr>
<td>34</td>
<td>15</td>
<td>22.165</td>
<td>0.94</td>
<td>0.84</td>
<td>1.2551</td>
<td>1.2662</td>
</tr>
</tbody>
</table>

Table 4: Idle Simulation Results for Old and New Battery Models
Then for both the 12V battery and the 36V battery, the specific gravity results were related to the corresponding state of charge results by plotting the corresponding state of charge versus specific gravity in Figure 8 and Figure 9.

![Diagram](image)

**Figure 8: Specific Gravity vs. State of Charge for 12V Battery Models**
The graph shows that specific gravity is linearly related to state of charge, which is what one expects in lead acid batteries. Therefore, this not only gives the quantitative relationship of specific gravity to state of charge; it also indirectly verifies the comparability of the results with the new battery model because it properly relates to the old model.

3.3.2 Generating State of Charge in Real Time

Previous simulations of the dual-voltage DC/DC converter architecture did not incorporate a state of charge based energy management algorithm, but instead a bus voltage regulated algorithm. Therefore, there was no need to develop a lead-acid battery model, which outputs the battery’s state of charge in real time. Effort was extended in order to develop a battery model that incorporated state of charge as one of its output pins.
Since the relationship between specific gravity and state of charge exists linearly, one can easily relate the two quantities and convert one to another. Using MAST, the Saber programming language, the new battery model called `batt_pb_1_w_sgmid` is coded so that the specific gravity parameter can be used in real time during simulations. This value is fed into a normalizing range component also designed using MAST to convert specific gravity to state of charge according to the results mentioned in the previous section. Figure 10 shows a diagram of the actual conversion components used in all simulations.

![Diagram of specific gravity to state of charge conversion](image)

(ah_nom=235, inom=3.264m, tend=72000, sg_full=1.2650, sg_diso=1.010)

**Figure 10: Specific Gravity to State of Charge Conversion**
3.4 Modeling the DC/DC Converter

The DC/DC converter used in the dual-voltage system was designed under Research Unit #1, DC/DC Converters for Dual-Voltage Electrical Systems. Though Research Unit #4 developed a detailed Saber model for the converter, the only important characteristic of the DC/DC converter desired in the simulations run under this project was the amount of current drawn by the converter as a function of the output voltage. Thus, the converter was treated as a black box with the I-V characteristic plotted in Figure 11.

**DC/DC Converter Characteristic**

![DC/DC Converter Characteristic Diagram](image)

**Figure 11: I-V Characteristic of the DC/DC Converter**

The amount of current that is drawn through the converter is a function of the voltage on the 14V bus, at the output of the converter. When the 14V bus is at a voltage greater than 14.2V, the converter will not supply additional current to the bus. When the voltage of the 14V bus is less than 13.8V, the converter will provide the maximum amount of current possible to the 14V bus. In between 13.8V and 14.2V, the amount of current drawn by the converter changes linearly between its maximum value and 0.5 amps. The only important characteristic of the DC/DC converter desired in the simulations run under this project is the amount of current drawn by the converter as a function of the output voltage.
voltage. The amount of current that is drawn through the converter is a function of the voltage on the 14V bus, at the output of the converter. When the 14V bus is at a voltage greater than 14.2V, the converter will not supply additional current to the bus. When the voltage of the 14V bus is less than 13.8V, the converter will provide the maximum amount of current possible to the 14V bus. In between 13.8V and 14.2V, the amount of current drawn by the converter changes linearly between its maximum value and zero amps.

The DC/DC Converter is the key component in implementing the state of charge based energy management algorithm. According to the state of charge energy management algorithm, the value of the maximum amount of current possible from the converter must be variable. In past simulations with the bus voltage based energy management algorithm, this maximum was fixed. The new DC/DC converter model must be able to vary its maximum current output according to the states of charge of both the 12V battery and the 36V battery. Thus, the new converter can be treated as a black box with an I-V characteristic like Figure 12.

![Figure 12: I-V Characteristic of DC/DC Converter Model in the State of Charge Energy Management System](image-url)
The arrow in the figure illustrates that the maximum current output of the DC/DC converter will vary. This variation is dictated by the state of charge based energy management algorithm previously explained in Section 2.2 The Energy Management Algorithm and Figure 2.

On the next page is the full dual-voltage system in the Saber simulator with the state of charge energy management system highlighted.
Figure 13: State of Charge Energy Management System (highlighted) in Dual-Voltage System in Saber
Chapter 4

Energy Management System Simulations

4.1 Running Simulations

The following sections will describe the three simulation situations considered. The idle case was used to investigate the performance of the alternator and batteries at low alternator shaft speed. The high-speed scenario was used to investigate the components’ performance at high alternator shaft speed. Finally, a city driving situation was used to study the variable-speed performance of the components.

4.1.1 The Simulation Process

Running a simulation required the input of simulation profiles consisting of drive cycles and load cycles into the design, specifying the alternator size, and setting the initial state of charge of batteries, temperature, handles of the algorithm, etc.

4.1.2 Simulation Profiles

To evaluate the power flow in the dual-voltage system, the system’s supply and demand of power under typical driving conditions needed to be simulated. This required the use of two types of data: drive cycles and load cycles. Drive cycles specify the car’s speed in kilometers per hour in one-second time increments. These standard drive cycles were used for the vehicle: 1) idling, 2) involved in continuous high speed driving and 3) involved in continuous city (stop-and-go) driving. Complimentary to drive cycles, load cycles are files that specify the sequence of load events, which will demand power from the electrical system. The three drive cycles available are: 1) worst-case summer conditions for idle, 2) worst-case summer conditions, and 3) worst-case winter conditions.
4.1.3 The Simulations Conducted

The following table shows the profiles for which simulations were run.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Drive Cycle</th>
<th>Load Cycle</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>idle.dat</td>
<td>idle.scs</td>
<td>Worst-case Summer</td>
</tr>
<tr>
<td>High-Speed</td>
<td>summer_const.dat</td>
<td>summer_worst_const.dat</td>
<td>Worst-case Summer</td>
</tr>
<tr>
<td>City Driving</td>
<td>ece15_city.dat</td>
<td>winter_worst_ece15.scs</td>
<td>Worst-case Winter</td>
</tr>
</tbody>
</table>

Table 5: Simulation Profiles

Each simulation profile carries a unique significance and was evaluated under profile-specific guidelines, as will be explained in the following sections.

4.2 Idle Simulations

One of the main conditions under which sizing can be performed is summer idling. It is not unreasonable to suppose a taxi idling for a significant amount of time while waiting for a passenger on a hot, rainy, summer day.

This section describes the parameters used when simulating an idling vehicle and the results obtained from Saber simulations.

4.2.1 Idle Parameters

Because the batteries are expected to discharge while the vehicle is idling, the initial state of charge of each battery is 1.0. In addition, since the load cycle used is a worst-case summer profile, the temperature used for the battery model is 40°C.

Each simulation simulated two hours of idle time. For each simulation, the idle.dat drive cycle and idle.scs load cycles were used. Idle.dat is a drive cycle in which, after start-up, the vehicle is continuously idling for two hours. Idle.scs is a worst-case summer load cycle (hot, raining, and nighttime).
4.2.2 Idle Simulation Results

Previous results without the state of charge energy management system is shown in Figure 14. The figure plots, for various battery Ah capacities, the final battery states of charge for each alternator used in the idle simulations.

![Figure 14: Idle Simulations without SOC Energy Management System: Final Battery SOC for Each Alternator Size](image)

Figure 14: Idle Simulations without SOC Energy Management System: Final Battery SOC for Each Alternator Size
As expected, the results with the state of charge energy management system implemented are nearly the same as the results obtained from bus voltage based energy management algorithm.

Figure 15: Idle Simulations with SOC Energy Management System: Final Battery SOC for Each Alternator Size

Like previous results without the more sophisticated energy management system, the current results show the trade-off involved in characterizing the alternator and the batteries. If a large enough alternator were used, a smaller-sized battery would suffice. However, if a smaller alternator were used, a larger battery would be needed.
4.3 High-Speed Driving Simulations

While the idle simulations are important in evaluating the system's ability to satisfy all power demands at one extreme, when the alternator shaft is rotating at idle speed, the high-speed simulations are used in evaluating the system's capabilities at the other extreme, when the alternator shaft is rotating at high speed.

This section describes the parameters used when simulating high-speed driving and the results obtained from the simulations.

4.3.1 High-Speed Parameters

Since the alternator is outputting close to its maximum amount of current possible, it is expected that the batteries will charge under high-speed driving conditions. To account for possible battery charging, the initial state of charge of both batteries is 0.9. Also, since a worst-case summer load cycle is used, the battery temperature is assumed to be 40°C.

Table 2 in Appendix B shows the load cycle, summer_worst_const.scs, with which high-speed driving simulations were run. Summer_worst_const.scs is a worst-case summer profile (hot, raining, and night-time) customized for the summer_const.dat drive cycle, in which the car is driving at a steady speed of 80 km/hr after start-up corresponding to an alternator shaft speed of approximately 6030 rpm.

4.3.2 High-Speed Driving Simulation Results

In evaluating the adequacy of components under the high-speed driving profile, one possible guideline might require the alternator and battery to supply all load power demands indefinitely. From previous results as seen in Table 6, the alternator would need to produce about 96A in order to satisfy all the loads sufficiently. It is important to note that it is the high-power speed-dependent future loads that are responsible for this high power requirement. The electromechanical engine valves alone require up to 2500W at high speeds, or almost 60A from the 42V alternator.
<table>
<thead>
<tr>
<th>Battery Capacity [Ah each]</th>
<th>100A</th>
<th>90A</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Ah</td>
<td>36V soc: increases 12V soc: increases</td>
<td>36V soc: decreases 12V soc: decreases</td>
</tr>
<tr>
<td>70 Ah</td>
<td>36V soc: increases 12V soc: increases</td>
<td>36V soc: decreases 12V soc: decreases</td>
</tr>
<tr>
<td>50 Ah</td>
<td>36V soc: increases 12V soc: increases</td>
<td>36V soc: decreases 12V soc: decreases</td>
</tr>
<tr>
<td>30 Ah</td>
<td>36V soc: increases 12V soc: increases</td>
<td>36V soc: decreases 12V soc: decreases</td>
</tr>
</tbody>
</table>

Table 6: High-Speed Driving Simulation without SOC Energy Management System Results

As expected, when the alternator produces more than the necessary 96A, as when a 100A-at-high-speed alternator is used, the batteries are charged, causing the battery states of charge to increase. If, however, a 90A-at-high-speed alternator is used, not enough current is being supplied to the loads by the alternator, and the batteries discharge, causing the states of charge to decrease.
<table>
<thead>
<tr>
<th>Battery Capacity [Ah each]</th>
<th>100A</th>
<th>90A</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Ah</td>
<td>36V soc: increases</td>
<td>36V soc: decreases</td>
</tr>
<tr>
<td></td>
<td>12V soc: increases</td>
<td>12V soc: decreases</td>
</tr>
<tr>
<td>70 Ah</td>
<td>36V soc: increases</td>
<td>36V soc: decreases</td>
</tr>
<tr>
<td></td>
<td>12V soc: increases</td>
<td>12V soc: decreases</td>
</tr>
<tr>
<td>50 Ah</td>
<td>36V soc: increases</td>
<td>36V soc: decreases</td>
</tr>
<tr>
<td></td>
<td>12V soc: increases</td>
<td>12V soc: decreases</td>
</tr>
<tr>
<td>30 Ah</td>
<td>36V soc: increases</td>
<td>36V soc: decreases</td>
</tr>
<tr>
<td></td>
<td>12V soc: increases</td>
<td>12V soc: decreases</td>
</tr>
</tbody>
</table>

Table 7: High-Speed Driving Simulation with SOC Energy Management System Results

As with the idle simulations, when the profile includes steady-state conditions such as a constant driving speed, simulations may not be necessary for a complete evaluation of the profile. When looking to see simply whether or not all the load demands are satisfied, as in the example guideline presented for the high-speed driving profile, the power and current estimates made by summing the values in the load cycle are sufficient in making that judgment. This result does not change with the new energy management system in place.
4.4 City Simulations

In sizing the power supply components, it is important to consider the stop-and-go city driving profile. Figure 16 shows the city drive cycle used in the city simulations.

![Figure 16: European Combined City and Highway Drive Cycle](image)

When the car spends a significant amount of time idling (possibly at street lights or in traffic), and then engages only in low-speed driving between stops, it may be difficult for the alternator to produce enough current to meet the demands of all the loads, particularly if heavy loads such as the heater or air conditioning are on.

This section describes the parameters used when simulating a vehicle engaged in city driving, the results obtained from Saber simulations, and the guidelines used to evaluate the results.

4.4.1 City Driving Parameters

City driving profiles usually consist of alternating idle times and low-speed driving. Idle times may account for 20% to 50% of the total drive time. In the city driving profile used here, ece15_city.dat, idle time accounts for 33% of the total drive cycle. In addition, ece15_city.dat includes speeds no higher than 50 km/hr. Because the
driving portions of the drive cycle allow the alternator to produce enough current to possibly charge the battery, the initial state of charge of both batteries is 0.9, allowing room for charging. Furthermore, since the load cycle used for the city simulations is a worst-case winter profile, the temperature used for the battery model is 0°C.

All simulations use the drive cycle ece15_city.dat, which alternates between idle and low-speed driving. Winter_worst_ece15.scs is the worst-case winter load cycle that is used.
4.4.2 City Simulation Results

Each automobile manufacturer has its own criteria for specifying sufficient battery and alternator size. Some automobile manufacturers might size the battery expecting it to discharge completely after many hours of city driving. Others may place restrictions only on the first couple of hours, perhaps requiring that the battery does not go below the initial state of charge after one or two hours of city driving. In this study the criterion is that the simulations must perform 10 hours of city driving before the batteries may discharge completely. Two hours of city driving were simulated, and the results were used to extrapolate the state of the batteries after 10 hours. Table 8 below shows previous simulations without the state of charge energy management system in place that were run, and the expected state of the batteries after 10 hours.

<table>
<thead>
<tr>
<th>42V Alternator Output [A at 1800 rpm - A at 6000 rpm]</th>
<th>60-120 A</th>
<th>54-108 A</th>
<th>50-100 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity [Ah each]</td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td>100 Ah</td>
<td></td>
<td>12V soc: completely discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td>70 Ah</td>
<td></td>
<td>12V soc: completely discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td>50 Ah</td>
<td></td>
<td>12V soc: completely discharged</td>
<td>12V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: completely discharged</td>
<td>36V soc: completely discharged</td>
</tr>
<tr>
<td></td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: completely discharged</td>
<td>12V soc: completely discharged</td>
</tr>
</tbody>
</table>

Table 8: City Simulations without SOC Energy Management System Results
Table 9 shows the new results with the state of charge energy management system running and one can see that with the SOC energy management system allows for smaller battery and alternator combinations to be used. This shows that this way of managing the energy in a dual-voltage system does improve the overall performance.

<table>
<thead>
<tr>
<th>42V Alternator Output [A at 1800 rpm – A at 6000 rpm]</th>
<th>60-120 A</th>
<th>54-108 A</th>
<th>50-100 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Capacity [Ah each]</td>
<td>100 Ah</td>
<td>70 Ah</td>
<td>50 Ah</td>
</tr>
<tr>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: ok, not yet discharged</td>
<td>36V soc: ok, not yet discharged</td>
<td></td>
</tr>
<tr>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td></td>
</tr>
<tr>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: ok, not yet discharged</td>
<td>12V soc: completely discharged</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: City Simulations with SOC Energy Management Results

The Table 8 and Table 9 entries which are labeled “ok, not yet discharged”, represent those alternator-battery combinations which meet the criteria outlined above. According to previous results, a 42V 54-108A alternator would suffice as long as the batteries had at least approximately 70 Ah capacity, but the new results show that the battery can have at least a capacity of 50 Ah.
4.5 Conclusions from Software Simulations

Previous analysis of the city simulations without the state of charge energy system centers on the control of the DC/DC converter current. The $I_{\text{max}}$ value for the DC/DC converter was set such that the long-term trend for both batteries would be the same: either both batteries charged or both batteries discharged. Though this long-term trend was attainable in the simulations, occasionally, for short periods of time, one battery could be charging while the other was discharging. Figure 17 below shows a portion of a typical plot, obtained from city simulations, of the battery states of charge versus time.

![Battery State of Charge Plot](image)

**Figure 17: Portion of Battery State of Charge Plot from City Simulations without State of Charge Energy Management System**

In previous simulations, with a fixed $I_{\text{max}}$, it is possible for one battery to charge at the expense of the other. Such results are not surprising considering the dynamic nature of the city profile; varying speeds not only affect the amount of current that the alternator
delivers to the dual-voltage system, but they also affect the power demanded by speed-dependent loads. This desire for more dynamic control of the DC/DC converter current confirms the need for an energy management algorithm to control the converter current. With the new energy management system in place, the behavior seen in Figure 17 does not occur.

From previous simulations without the state of charge energy management system implemented, the results show that one can not easily choose an alternator-battery combination that would result in the desired average power supply needed. Whereas the steady-state estimates in the idle and high-speed load cycles were sufficient in determining the alternator size which would supply all demands, the load cycle estimate alone is not enough to determine the alternator-battery combination which would satisfy all city driving demands. Intermittent loads such as the turn signals and brakes, combined with the effects of varying car speed on speed-dependent load consumption and alternator output, make it difficult to specify an exact power requirement for city conditions. Consequently, simulations are indeed useful in studying the system requirements when varying conditions are involved, and when a steady-state estimate will not suffice. Furthermore, a more sophisticated energy management algorithm does better service the demands of on and off city driving.

The city simulation results provide the most limiting information for specifying the batteries and alternator [5]. According to previous results, the smallest possible alternator size that can be used is a 54-108A alternator whereas with the state of charge energy management system, an alternator of size 50-100A can be used in combination with a 70Ah battery. Implementing the state of charge energy management system in the dual-voltage system dramatically improves cost and size of the entire automobile electrical system and therefore the performance of the car.
Chapter 5

Testing the System in Hardware

In order to validate the energy management algorithm that is discussed in this proposal, it is necessary to construct a physical test facility on which tests can be conducted. This facility needs to be an easily controllable and modifiable electrical equivalent of the 42V / 14V uni-directional DC/DC converter architecture from Figure 1. This breadboard facility can be broken down into 3 major parts: 1) power delivery systems, 2) power dissipating systems, and 3) control systems.

The breadboard power delivery system includes the batteries, the alternator and its support equipment, the DC/DC converter and the cables necessary to deliver power to the loads. Loads that can dissipate a total of about 4100 watts including fixed resistance loads and speed dependent loads are parts of the power dissipating system. The 4100 watts dissipated are well above the maximum alternator output of 3600 watts at high alternator rpm so that implementation of an energy management algorithm is relevant in the setup. Lastly, the control system consists of a PC master control system with a virtual driver implemented using LabView 5.0. The input and output of information is done via CAN buses and stored in data collection modules. There is a breadboard interface that receives PC input load cycle and drive cycle files that come directly from the Saber simulations.

5.1 The Loads

In the case of the breadboard facility, loads can be broken down into two different categories. The first type of load is a fixed resistance load, and the second type of load is a speed-dependent load. In order to match the breadboard loads with those in the Saber simulator, a nominal power versus time chart was prepared from the load cycle profiles used in Saber then converted into LabView code and read by the control systems to achieve the same load profile in the breadboard facility.
The fixed resistance load per unit time can be achieved with a combination of huge metal resistors. The resistors were held in aluminum mounts and power flow to the resistors was controlled by a microcontroller power MOSFET. Each MOSFET provides as an output on one of its pins a current that is proportional to the amount of current flowing through its channel. The MOSFETs were mounted to custom designed boards. Also mounted to each board was a LM 317 voltage regulator that was used to provide power to the CAN microcontroller that was controlling the state of the MOSFET via instructions it was receiving over the CAN bus.

The breadboard also needed several speed-dependent loads enabled. These were implemented using a Hewlett Packard 6050A 1800Watt Programmable Load that was configured to draw a current proportional to the speed of the alternator. The amount of current it demanded was varied with alternator speed. It has a minimum demand of 9 amps at idle (alternator speed of 1800 rpm) and a maximum of 45 amps at higher speeds (alternator speed of 6000 rpm or more). The HP 6050A received control commands over a GPIB bus.

5.2 The Alternator

The alternator used to provide power to the network was a 40V Bosch alternator that was given to the MIT Consortium by Paul Nicastri of Ford. The alternator can supply 50 amps at idle and 100 amps at higher rpm. Thus the alternator can supply a maximum of 2000 watts at idle and 4000 watts at higher rpm.

In a conventional automobile, the alternator is spun by the car’s engine. It is geared at a ratio of approximately 3 alternator rotations for every one engine rotation. The situation is the same with the breadboard facility. The alternator is controlled by an 18hp 13.4kW Pacific Scientific PacTorq Brushless P.M. Servomotor. The servomotor and the alternator were geared so that one rotation of the servomotor produces about 3 rotations of the alternator. A Pacific Scientific 756 ServoController controlled the speed of the motor. The controller is controlled through its serial port, and for testing purposes, it is being software limited by its control program, ‘PacTorq.bas’, to spinning the PacTorq
motor to 3500 rpm. If this limit is exceeded, the motor stops all motion and cannot move again until it is reprogrammed.

Because the donated alternator is a 40V alternator, it needed to be converted into a 42V alternator in order to be used in the 42V-14V dual-voltage automobile electrical system. In order to do this, the regulator from the Bosch alternator was removed and the voltage sensing lead was disconnected from the 42V bus. Then a 180Ω resistor was connected in series with the 42V bus and the sensing lead of the regulator. This makes the sensing node of the regulator detect a voltage that is two volts less that the voltage of the 42V bus which converts the alternator into a 42V alternator.

5.3 The DC/DC Converter

The breadboard’s DC/DC Converter is a unidirectional converter that is capable of delivering up to 68 amps to the 14V bus. The DC/DC converter can be controlled to deliver an amount of current less than its instantaneous maximum deliverable power. The converter can supply \( I_{\text{max}} \) but it can also supply any amount of current less than \( I_{\text{max}} \). The converter, however, cannot be controlled to deliver an amount of current greater than its regulation characteristic will allow. For example, if the 14V bus were at 14.0V (it is regulated to 14.2V) then the maximum amount of current that the converter could deliver is 34 amps. It cannot be controlled in any way to deliver more than 34 amps, but it can be controlled to deliver any amount of current less than 34 amps. Changing the value that appears on its 8-bit input, according to the energy management algorithm’s specifications can set the current limit of the DC/DC converter.
5.4 The Batteries

The 36V battery was made up of 3 AC Delco Professional Freedom Car and Truck 58-5YR batteries connected in series. They have a reserve capacity of 70 minutes. The 12V battery was an AC Delco Professional Freedom Car and Truck 65-7YR battery. It has a reserve capacity of 160 minutes. They are both 70Ah batteries.

5.5 Control System

Because the breadboard facility cannot be driven, a method of simulating driving had to be created. This virtual driver was implemented using LabView 5.0. The virtual driver was coded in LabView’s multithreaded ‘G’ graphical programming language and run on a 200 MHz Pentium PC. The virtual driver had to be able to turn on and off fixed resistance loads, control the amount of current drawn by the DC/DC converter, control the speed of the alternator, and collect information about the state of the system. A subprogram was written to control each of these functions, and these subprograms were combined together in the file “finalcircuit.vi”. “EMValve.vi” controls the current drawn by the DC/DC converter and “PacSciByte.vi” controls the speed of the alternator. Information going to and received from the CAN bus is controlled by “SerialController.vi”. Information is sent through the CAN bus to the PC, so the CAN bus is the means of collection of information about the state of the system.

The State of Charge Energy Management System was not written in ‘G’, but in C, to allow easy changeability. This also allows for people who are not familiar with LabView’s programming language to understand the system. A Code Interface Node in LabView is built to interface the C code with the entire LabView program. After the Code Interface Node is established in finalcircuit.vi, one can easily convert the C program to work in LabView by importing it to the Code Interface Node when the tests are ready to run. Because the State of Charge Energy Management System was written in C, it also made it possible for the energy management system in Saber to be the same as the one in the breadboard.

The breadboard facility’s state of charge energy management system differed from that of Saber in one way. In Saber, the battery models did give their state of charge
without having to deduce the state of charge from the voltages or currents. However, in the breadboard facility, there is no way to determine the states of charge of the batteries except by integrating the battery currents over time. Since the information on the control system is collected every second, the states of charges of the batteries could be calculated by first adding or subtracting amp-seconds from the initial amp-hours if the battery currents were positive (into the battery) or negative (out of the battery) respectively. Then these values were divided by the initial battery amp-hour capacities to obtain states of charge for both batteries in real time. These values are valid because there are no leakage currents due to temperature over the short intervals of testing (less than 3 hours).
Chapter 6

Energy Management System Breadboard Tests

6.1 Running Tests

6.1.1 Test Procedures

The goal is to understand and successfully run the same experiments on the breadboard facility as the simulations in Saber. Here are the experimental procedures:

1. Implement an energy management algorithm
2. Select a drive cycle to use with it
3. Select an appropriate electrical load cycle for the selected drive cycle
4. Convert the drive cycle and load cycle into breadboard input files
5. Run the breadboard input files on the breadboard facility
6. Analyze collected data and compare with Saber simulations

The data to be collected is open circuit battery voltages before test, battery voltages during test, and the state of charge of the batteries during and after the test.

6.1.2 Test Profiles

To evaluate the power flow in the dual-voltage system, the system’s supply and demand of power under typical driving conditions needed to be simulated. This required the use of two types of data: drive cycles and load cycles. Drive cycles specify the car’s speed in kilometers per hour in one-second time increments. Drive cycles were used for the vehicle: 1) idling, 2) involved in continuous high speed driving and 3) involved in continuous city (stop-and-go) driving. Complimentary to drive cycles, load cycles are files that specify the sequence of load events that will demand power from the electrical system. The three drive cycles available are: 1) worst-case summer conditions for idle, 2) worst-case summer conditions, and 3) worst-case winter conditions. These are the same drive cycles and load cycles as the ones in the Saber simulations except they were converted in LabView format.
6.1.3 Tests Run

The following table shows the profiles for which tests were run.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Drive Cycle</th>
<th>Load Cycle</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>Idle.dat</td>
<td>idle.scs</td>
<td>Worst-case Summer</td>
</tr>
<tr>
<td>High-Speed</td>
<td>Summer_const.dat</td>
<td>summer_worst_const.dat</td>
<td>Worst-case Summer</td>
</tr>
<tr>
<td>City Driving</td>
<td>Ece15_city.dat</td>
<td>winter_worst_ece15.scs</td>
<td>Worst-case Winter</td>
</tr>
</tbody>
</table>

Table 10: Tests and Corresponding Profiles for the Breadboard Facility

Each test profile carries a unique significance and was evaluated under profile-specific guidelines, as will be explained in the following sections.

As mentioned in Section 5.5 Control System, the need to determine the states of charge for both batteries requires that the batteries be fully charged to begin with, so for all profiles tested, the initial state of charge of the batteries are both 1. In the simulations the temperature used for the battery model can be easily changed, but in the case of the a physical testing facility it is impossible to do that, so the temperature is noted to be room temperature for each breadboard test. Each test runs for two hours.
6.2 Breadboard Test Results

The results from the idle and high-speed driving tests were exactly what were expected from the simulation results. In the idle case, shown in Figure 18, for the 70Ah batteries with the 50A idle alternator output we had, the final state of charge was above 60% as interpolated from the simulation results in Figure 15.

![Idle Tests with State of Charge Energy Management System: Battery States of Charge Vs. Time](image)

Figure 18: Idle Tests with State of Charge Energy Management System: Battery States of Charge Vs. Time

For the high-speed driving test results, since the alternator used is only capable of outputting 100A at high speeds, the simulation results show that the state of charge would increase over time. Indeed, this reflects the results obtained from the high-speed breadboard tests.
Not only did the results from the idle and high-speed cases agreed with the simulations, but the city driving results also confirmed the simulation results. For the combination of batteries and alternator in the breadboard facility, the simulations show that without the state of charge energy management system, the final states of charge of the batteries were not acceptable, however, with the system in place, the combination is indeed acceptable.

Figure 19: City Test and Simulation without SOC Energy Management System: 12V Battery State of Charge Vs. Time
6.3 Conclusions from Hardware Tests

The breadboard facility tests confirmed the results from Saber simulations. Not only did they confirm simulation results; it also supports the use of the state of charge energy management algorithm in an energy management system. The tests also verify that the dual-voltage system indeed benefits from an energy management system.
Chapter 7

Simulation of New High Power Alternator

Another way to manage energy in the dual-voltage system is to change the alternator output control strategy. As mentioned, the city simulation results show the difficulty involved in specifying the alternator when changing vehicle speeds cause the alternator output to vary. The characteristic curve of typical alternators shows the dependency of alternator output current on alternator shaft speed, and thus on vehicle speed. Choosing an alternator whose average output satisfies a given requirement is not a straightforward calculation. This difficulty leads to the possibility that an alternator whose characteristic curve shows more constant power output capabilities over the ranges of common car speeds might be beneficial. It would be simpler to pick such an alternator for profiles involving varying car speeds and benefits the usage of energy in a dual-voltage system.

Through the use of a simple switched-mode rectifier, a new load-matching technique for automotive alternators is introduced that allows substantial increases in the output power capability and efficiency. Under Research Unit #2 such an alternator was proposed by Dave Perreault and Vahe Caliskan in a report called “Automotive Power Generation and Control,” Massachusetts Institute of Technology Laboratory for Electromagnetic and Electronic Systems Technical Report TR-00-003, May 2000. High power is achieved using the switched-mode rectifier as a second control handle to properly match the load to the alternator. The basic concept is that using the switched-mode rectifier, one can cause the waveform seen by the conventional alternator to be much lower than what it really is at the output. The waveform has an average value that is dependent on the output voltage and the duty ratio of the pulse caused by the rectifier. In an averaged sense, the boost switch set acts as a dc transformer with a turns-ratio controlled by the pulse-width modulation (PWM) duty ratio. The PWM frequency is much higher than the ac frequency allowing the alternator machine and diode-bridge to react to the average value of the waveform generated. As a result, one has an extra
control handle to make the alternator generate up to its maximum power as speed varies [7]. The figure below shows such a scheme.

![Diagram of alternating current and field current regulator](attachment:image.png)

Figure 21: Load-matched Alternator: (a) matching stage inserted in an alternator, (b) representative waveforms

It uses a conventional averaged 14V alternator model with inputs of the duty-ratio factor as calculated in “Automotive Power Generation and Control,” Massachusetts Institute of Technology Laboratory for Electromagnetic and Electronic Systems Technical Report TR-00-003 [7] and shaft speed. The results from incorporating this alternator into the dual voltage architecture will be very interesting. Therefore, a Simulink model is generated and studied for this load-matching alternator. It is developed using this simplified circuit of the load-matched alternator:
Where \( E = k\omega i_f \), \( Z(\omega) = \sqrt{R_s^2 + \left(\frac{\pi}{30} (p/2) \omega L_s\right)^2} \), and \( 0 \leq \gamma \leq 1 \)

\[
V_p = \gamma V_s \\
i_p = \frac{1}{\gamma} i_s \\
i_s = \gamma i_p = \gamma \left(\frac{E - \gamma V_s}{Z(\omega)}\right)
\]

So output power \((P_s)\) can be written as:

\[
P_s = \frac{\gamma E V_s - \gamma^2 V_s^2}{Z(\omega)}
\]

To achieve the goal of maximum power through the control of duty ratio \((\gamma)\), one can take the derivative and set the equation equal to zero to find the formula for the control variable \(\gamma\):

\[
\max_{\gamma} P_s \rightarrow \frac{\partial P_s}{\partial \gamma} = 0 \rightarrow \frac{E V_s - 2\gamma V_s^2}{Z(\omega)} = 0
\]

When power is maximized the duty ratio gamma \((\gamma)\) is found to be:

\[
\gamma = \frac{E}{2V_s} \quad \text{Or} \quad \gamma(\omega, i_f, V_s) = \frac{k\omega i_f}{2V_s}
\]
To simplify the circuit even further so a model can be developed in Simulink without modeling the complicated DC transformer, a thevenin equivalent of the circuit is calculated below. In a thevenin equivalent circuit $V_s$ would compose of a thevenin equivalent voltage source ($V_{TH}$) in series with a resistor ($R_{TH}$) which yield equation (7):

$$ V_s = V_{TH} + R_{TH} i_s \quad (7) $$

With equation (1) expressing $V_p$ in terms of the above variables would yield equation (8):

$$ V_p = \gamma V_{TH} + \gamma R_{TH} i_s = \gamma V_{TH} + \gamma^2 R_{TH} i_p \quad (8) $$

With equation (8) the thevenin circuit to the circuit in Figure 22 appears in Figure 23 below:

![Figure 23: Thevenin Equivalent of New High-Power Load-Matching Alternator Model](image)

This circuit can be then used to find the expression of the source voltage $E$:

$$ \frac{E}{2} = \gamma V_{TH} + \gamma^2 R_{TH} \left( \frac{E - \gamma V_{TH}}{Z(\omega) + \gamma^2 R_{TH}} \right) \quad (9) $$
The thevenin circuit and its dependencies are modeled in Simulink. In simulation the power that is required \( (P_s) \) and the speed of the alternator \( (\omega) \) are fixed, all that need to be found using Simulink are the field current \( i_f \) and the duty ratio \( (\gamma) \) to achieve power supply and efficiency.

Simple controls for \( \gamma \) and \( i_f \) are:

\[
T_1 \dot{\gamma} = -\gamma + \frac{E}{2V_s} \tag{10}
\]

\[
T_2 \dot{i}_f = 100(V_{sn} - V_s) \text{ where } V_{sn} = 42 \text{ Volts} \tag{11}
\]

Constants \( R_{TH}, V_{TH}, k, R_s, L_s \) are defined in a Matlab file using values from the alternator model developed under Research Unit 4. These values and how they are obtained can be found in "Modeling and Simulation of a Claw-Pole Alternator: Detailed and Average Models," LEES Technical Report TR-00-009 by Vahe Caliskan [8]. \( T_1 \) and \( T_2 \) are time constants defined by the user with the requirement that \( T_2 \) be greater than \( T_1 \) because the system required that the duty ratio react faster than the field current. They are fixed arbitrarily to be \( T_1 = 0.1 \) and \( T_2 = 1.0 \). Below is the full alternator model in Simulink.

Figure 24: Actual Simulink Model
Where:

\[ V_s = \frac{ER_{TH} \gamma + Z(\omega) V_{TH}}{R_{TH} \gamma^2 + Z(\omega)} \]  

(12)

\[ Fcn = \frac{E}{2V_s} \]  

(13)

\[ E = I_f \omega k \]  

(14)

\[ Fcn1 = 100(V_{sn} - V_s)/T_2 \ , \ V_{sn} = 42 \text{ Volts} \]  

(15)

To verify the simulation results, calculations for the field current \((i_f)\) and the duty ratio \((\gamma)\) are done. The duty ratio was found earlier to be:

\[ \gamma = \frac{E}{2V_s} \]  

(6)

Below are calculations for the field current \(i_f\).

\[ P_s = \frac{E^2}{2Z(\omega)} - \frac{E^2}{4Z(\omega)} = \frac{E^2}{4Z(\omega)} = \frac{(k \omega i_f)^2}{4Z(\omega)} \]  

(16)

\[ i_f = \sqrt{\frac{P_s 4Z(\omega)}{k^2 \omega^2}} \]  

(17)

\[ V_p = \frac{E \gamma^2 R_{TH} + \gamma V_{TH} Z(\omega)}{Z(\omega) + \gamma^2 R_{TH}} \]  

(18)

\[ V_s = \frac{1}{\gamma} \left( \frac{E \gamma^2 R_{TH} + \gamma V_{TH} Z(\omega)}{Z(\omega) + \gamma^2 R_{TH}} \right) = \frac{ER_{TH} \gamma + V_{TH} Z(\omega)}{Z(\omega) + \gamma^2 R_{TH}} \]  

(19)

Use this to solve for \(i_f\):

\[ i_f = \sqrt{\frac{4ZV_s(V_s - V_{TH})}{k^2 \omega^2 R_{TH}}} \]  

(20)
The rest of this chapter presents the graphs of the resulting parameters from one sample simulation of the load-matching alternator model in Simulink. Values used come directly from "Modeling and Simulation of a Claw-Pole Alternator: Detailed and Average Models," LEES Technical Report TR-00-009 by Vahe Caliskan [8].

\[ V_{TH} = 27.0 \text{Volts}, R_{TH} = 0.75 \Omega \]
\[ \omega = 3000, k = 0.00429, R_s = 0.033, L_s = 0.000177, p = 12 \]

Using these values and the results from the simulations for \(i_f\), calculations show that \(E\) would equal 33.46 Volts. The results show that the model for the load-matching alternator is indeed stable and the values correspond to the hand calculations done.

Figure 25: Modeled Source Voltage \(E\)
Figure 26: Duty Ratio Gamma ($\gamma$)

Figure 27: Field Current $i_f$
These simulations demonstrate that this technique of modifying the alternator can be useful in an energy management system for a dual-voltage application. This is a worthwhile scheme for further exploration.
Chapter 8

Conclusion

8.1 Discussion and Comparison of Results

The final state of charge that is acceptable for the starting battery might vary according to each car manufacturer’s guidelines. In some cases, a state of charge of 0.6 might be considered the lowest state of charge that will guarantee start-up on a subsequent drive; a lower state of charge may or may not be sufficient, depending on environmental and load cycle conditions of the subsequent drive. Perhaps a state of charge of 0.25 could be considered the lowest state of charge below which vehicle start-up is not possible. Each manufacturer might prefer to determine its own state of charge values of interest.

As presented above, each automobile manufacturer may wish to impose its own internal specification guidelines, and the criteria set by different manufacturers may not necessarily be compatible with each other. The challenge in characterizing the power supply components in the dual-voltage system will be in determining which guidelines should be used as the limiting case, which in this study is the city drive cycle.

No matter what guidelines an automobile manufacturer imposes on their vehicles’ components, the most important conclusion from this thesis is that an energy management system based on state of charge is a tremendous benefit to the dual-voltage automotive system. Through simulation and actually laboratory testing, the need for this energy management system is clearly demonstrated. Not only that, now anyone can use this basic model to simulate and test their specific components on an overall system level performance standard. Simulating the physical system proves to be useful. By looking at the automotive electrical system as a whole, one can gain tremendous “savings” in the subsystems and parts.
8.2 Further Study

In Section 3.3 Modeling the Lead-Acid Battery, it was mentioned that the battery model used in the Saber design of the dual-voltage system is encrypted. Since the code underlying the model is encrypted, it is not known exactly how the lead-acid battery is modeled. The Saber battery model should be tested against actual battery performance used in the MIT breadboard facility, or another well tested, fully known battery model should be used in the design. Further work on this project would benefit from an in-depth study of lead-acid battery models.

Component specification is not limited to the three profiles discussed in this thesis, which represent, respectively, the extreme cases of continuous worst-case stop-and-go driving, continuous low alternator shaft speed, and continuous high alternator shaft speed. Further study should investigate other possible scenarios that might provide insight into the power demands of the dual-voltage system. For example, a drive cycle including both city and high-speed driving might be useful in studying the power requirements involved in replenishing a battery that has been discharging since vehicle start-up.

Other control handles for the energy management system includes field winding current control and load management control. The alternator of the dual-voltage system can be altered such that its behavior is dependent on the state of charge of the batteries. When the system detects a substantial discharge of the batteries, certain loads can be shut off or turned down in order to conserve energy used.

Furthering the energy management system could be a system that predicts the amount of energy or time left of usage in the batteries. A readout in the car can provide occupants information on how much more energy is left in the batteries. A warning light can go off to notify drivers to shed loads. These are all relevant topics to look at in the future.
References


Appendix A

System Models

A.1 MAST code for the Dual Voltage System
new_loads_convsimp.sin

```
# Saber netlist for design new_loads_convsimp
# Created by the Saber Integration Toolkit 5.1-3.3 of Analogy, Inc.
#
#
 Instances found in the top level of design new_loads_convsimp
#
#

sdrprsq.sdr starter pos:pos_starter = posseq=[(0,2), (3,1)]
r.batt_42V_cable p: n2395 m: n2237 = rnom=1.5m
sdrprsq.sdr parking lights pos:pos_parking = posseq=[(0, 1)]
short.i 42V batt p: n2395 m:batt_42V
r.alt_cable_p n2370 m:v_to_bus_42V = rnom=1.5m
sdrprsq.sdr wipers pos:pos_wipers = posseq=[(0,1)]
sdrprsq.sdr brakes pos:pos_brakes = posseq=[(0,1)]
short.i_wipers p:bus_42V m: n1687
short.i_starter p:bus_42V m:starter
short.i_speed_deph_42V p:bus_42V m: n2015
sdrprsq.sdr turn pos:pos_turn = pposseq=[(0,1)]
short.i_alt p:alternator m: n2370
sdrprsq.sdr radio pos:pos_radio = posseq=[(0,1)]
short.i_radio p:bus_42V m: n1685
short.i_ps_cmp_blwr p:bus_42V m: n653
sdrprsq.sdr_ps_cmp_blwr pos:pos_ps_cmp_blwr = posseq=[(0,1)]
sdrprsq.sdr defog pos:pos_defog = posseq=[(0,1)]
short.i_seat_htrs p:bus_42V m: n836
sdrprsq.sdr_seat_htrs pos:pos_seat_htrs = posseq=[(0,1)]
short.i_base_loads_42V p:bus_42V m: n840
sdrprsq.sdr climate pos:pos_climate = posseq=[(0,1)]
sdrprsq.sdr cruise pos:pos_cruise = posseq=[(0,1)]
short.i_defog p:bus_42V m: n917
short.i_parking p:bus_14V m: n923
short.i_parking_and_lowbeams p:bus_14V m: n1585
short.i_base_loads_14V p:bus_14V m: n918
short.i_turn p:bus_14V m: n924
short.i_brakes p:bus_14V m: n1698
```
short.i_cruise p:bus_14V m:_n927
short.i_climate p:bus_14V m:_n928
sdr_prsq.sdr_sunroof pos:pos_sunroof = posseq=[(0,1)]
short.i_windows p:bus_42V m:_n1681
short.i_sunroof p:bus_42V m:_n1683
sdr_prsq.sdr_windows pos:pos_windows = posseq=[(0,1)]
sdr_prsq.sdr_windshield pos:pos_windshield = posseq=[(0,1)]
short.i_windshield p:bus_42V m:_n1015
alt42v_avg_0.alt42v_avg_0_1 bp:alternator bm:0 shaft:shaftspeed_radps \
data:ilmax = rf=3.44, k=0.004107402290, ls=0.0005754574644, \
rs=0.2719090709
short.i_42V_bus p:v_to_bus_42V m:bus_42V
short.i_14V_bus p:_n2298 m:bus_14V
short.i_mirrors p:bus_14V m:_n1223
sdr_prsq.sdr_mirrors pos:pos_mirrors = posseq=[(0,1)]
short.i_cd p:bus_14V m:_n1694
sdr_prsq.sdr_cd pos:pos_cd = posseq=[(0,1)]
short.i_phone p:bus_14V m:_n1696
sdr_prsq.sdr_phone pos:pos_phone = posseq=[(0,1)]
sdr_prsq.sdr_rear_seat_htrs pos:pos_rear_seat_htrs = posseq=[(0,1)]
short.i_rear_seat_htrs p:bus_42V m:_n1257
short.i_nav_aid p:bus_14V m:_n1272
sdr_prsq.sdr_nav_aid pos:pos_nav_aid = posseq=[(0,1)]
short.i_actsuspension p:bus_42V m:_n1351
sdr_prsq.sdr_actsuspension pos:pos_actsuspension = posseq=[(0,1)]
sdr_prsq.sdr_act_eng_mount pos:pos_act_eng_mount = posseq=[(0,1)]
short.i_act_eng_mount p:bus_42V m:_n1354
short.i_speeddep_14V p:bus_14V m:_n2018
load_res."Active Engine Mount" p:_n1354 m:0 pos:pos_act_eng_mount = \
vnom=42, \n  pwr=70
load_res."Active Suspension" p:_n1351 m:0 pos:pos_actsuspension = \
vnom=42, \n  pwr=1000
load_res."Heated Rear Window" p:_n917 m:0 pos:pos_defog = vnom=42, \
pwr=280
load_res."Heated Windshield" p:_n1015 m:0 pos:pos_windshield = vnom=42, \
pwr=700
load_res."Seat Heaters" p:_n836 m:0 pos:pos_seat_htrs = vnom=42, \
pwr=110+2
sdr_prsq.sdr_base_loads_42V pos:pos_base_loads_42V = posseq=[(0,1)]
load_res."Power Mirror Heaters" p:_n1223 m:0 pos:pos_mirrors = vnom=14, \
pwr=30
load_res."Turn Lights" p:_n924 m:0 pos:pos_turn = vnom=14, pwr=110.8
load_res."High Beam Headlamps" p:_n1580 m:0 pos:pos_highbeams = \
vnom=14, pwr=130
load_res."Base Loads 14V" p:_n918 m:0 pos:pos_base_loads_14V = vnom=14, \
pwr=187.8
sdr_prsq.sdr_base_loads_14V pos:pos_base_loads_14V = posseq=[(0,1)]
load_res."All Parking Lights" p:_n923 m:0 pos:pos_parking = vnom=14, \
pwr=94.2
load_res."Parking and Lowbeams" p:_n1585 m:0 pos:pos_parking_and_lowbeams = \n
vnom=14, pwr=204.2
sdr_prsq.sdr_parking_and_lowbeams pos:pos_parking_and_lowbeams = posseq={(0,1)}
short.1_air_cond p:bus_42V m:_n1648
sdr_prsq.sdr_air_cond pos:pos_air_cond = posseq={(0,1)}
load_res."Base Loads 42V" p:_n840 m:0 pos:pos_base_loads_42V = vnom=42, pwr=92
load_power."Power Windows" p:_n1681 m:0 pos:pos_windows = imaxval=100, vnom=42, vnom=270
load_power."Sun Roof" p:_n1683 m:0 pos:pos_sunroof = imaxval=100, vnom=42, pwrval=190
load_power."Radio/Subwoofer" p:_n1685 m:0 pos:pos_radio = imaxval=100, vnom=42, pwrval=40
load_power."Antenna Lift" p:_n1692 m:0 pos:pos_antenna = imaxval=100, vnom=14, pwrval=45
load_power."CD Changer" p:_n1694 m:0 pos:pos_cd = imaxval=100, vnom=14, pwrval=13
load_power.Brakes p:_n1698 m:0 pos:pos_brakes = imaxval=100, vnom=14, pwrval=470.6
load_res."Water Pump" p:_n1831 m:0 pos:pos_water_pump = vnom=42, pwr=300
load_power."Emissions Air Pump" p:_n1834 m:0 pos:pos_emissions = imaxval=100, vnom=42, pwrval=150
load_power."Automatic Climate Control" p:_n928 m:0 pos:pos_climate = vnom=14, pwr=25
load_power."Navigation Aid" p:_n1272 m:0 pos:pos_nav_aid = vnom=14, pwr=50
load_power."All Weather Night Vision" p:_n1278 m:0 pos:pos_night_vision = vnom=42, pwr=100
load_power."ABS/TC" p:_n1874 m:0 pos:pos_abs_tc = imaxval=100, vnom=14, pwrval=324
load_power."Automatic Tire Pump" p:_n1870 m:0 pos:pos_tire_pump = imaxval=100, vnom=14, pwrval=100
load_power."Cruise Control" p:_n927 m:0 pos:pos_cruise = vnom=14, pwr=25
load_speed_42."Speed Dep Base Loads 42V" p:_n2016 m:0 \ shaft_rpm:shaftspeed_rpm = idlepwr=211.2, maxpwr=250.6
load_reslevel.Vent \[p: n_653\] \[m:0\] \[pos:pos_ps_cmp_blwr = pwrhigh=300, pwrmed=195, pwrlow=100, \]
\[vnom=42\]
load_reslevel."Air Conditioning" \[p: n_648\] \[m:0\] \[pos:pos_air_cond = pwrhigh=350, pwrlow=150, pwrmed=245, vnom=42\]
load_reslevel.Heater \[p: n_839\] \[m:0\] \[pos:pos_heater = pwrhigh=300, pwrmed=195, vnom=42\]
load_reslevel."Rear Seat Heaters" \[p: n_257\] \[m:0\] \[pos:pos_rrear_seat_htrs = pwrhigh=250, pwrmed=150, pwrlow=90, vnom=42\]
load_currlevel."Windshield Wipers, Front" \[p: n_687\] \[m:0\] \[pos:pos_wipers = pwrhigh=150, pwrmed=90, pwrlow=30, vnom=42\]
short.i_converter_out \[p:v_converter_out\] \[m:n2291\]
\[r.conv_cable \[p:n2291\] \[m:n2298\] = rnom=1.5m\]
short.i_converter_in \[p:n2296\] \[m:v_converter_in\]
\[sdr_prsq.sdr_converter pos:n2293 = posseq=[\{0,1\}]\]
sw_lp2t.sw_converter \[p:n2293\] \[com:n2296\] \[p2:v_to_bus_42V\] \[pl:n2288\] = roff=inf, \[tdbrk=.1, rfunc=cont, ron=0, tdmk=1\]
v_dc.v_dummy \[p:n2288\] \[m:0\] = dc_value=38
r.path \[p:n2288\] \[m:0\] = rnom=lmeg
sdr_prsq.sdr_ac_compressor \[pos:pos_ac_compressor = posseq=[\{0,1\}]\]
short.i_ac_compressor \[p:bus_42V\] \[m:n2358\]
load_powerlevel."A/C Compressor Pump" \[p:n2358\] \[m:0\]
pos:pos_ac_compressor = \[pwrhigh=4000, pwrmed=2000, pwrlow=3000, vnom=42\]
sdr_prsq.sdr_catalytic \[pos:pos_catalytic = posseq=[\{0,1\}]\]
short.i_catalytic \[p:bus_42V\] \[m:n2400\]
load_power."Heated Catalytic Converter" \[p:n2400\] \[m:0\]
pos:pos_catalytic = \[imaxval=100, vnom=42, pwrval=3000\]
batt_pb_1_w_soc\[.batt_pb_1_w_soc1\] \[p:batt_42V\] \[m:0\] \[soc:n2556 = ahrated=70, \]
\[inom=70/200, vnom=12.6*3, n_cell=6*3\]
batt_pb_1_w_soc\[.batt_pb_1_w_soc2\] \[p:batt_14V\] \[m:0\] \[soc:n2552 = ahrated=70, \]
\[inom=70/200\]
dcdc_emsl.dcdc_emsl \[out:v_converter_out\] \[in:v_converter_in\] \[com:0\]
\[emn:n2558\]
ems.emsl \[emn_out:n2558\] \[soc_12v:n2552\] \[soc_36v:n2556\] \[emn_in:n2558\]

A.2 MAST code for State of Charge Energy Management System

ems.sin

\text{element template ems soc_12v soc_36v emn_in emn_out = imax, imin, step}\n
\text{input nu soc_12v, soc_36v, emn_in}\n\text{output nu emn_out}\n\text{number imax=68, imin=0.5, step=1}\n\{\n  \text{if (soc_12v} \geq 1.15) \text{emn_out = imin}\n  \text{else if (soc_12v} \geq 1.05 \& soc_12v < 1.15) \text{emn_out = imin}\n  \text{else if (soc_12v} \geq .90 \& soc_12v < 1.05)\{\n    \text{if (soc_36v} \geq 1.05) \text{emn_out = imax}\n\}
else if (soc_36v >= .90 & soc_36v < 1.05) emn_out = emn_in
else if (soc_36v >= .5 & soc_36v < .90) {
    if (emn_in ~= imin) emn_out = emn_in - step
}
else emn_out = imin
else if (soc_36v >= .5 & soc_36v < .90) {
    if (soc_36v >= 1.05) emn_out = imax
else if (soc_36v >= .90 & soc_36v < 1.05) {
    if (emn_in ~= imax) emn_out = emn_in + step
}
else if (soc_36v >= .5 & soc_36v < .90) {
    if (emn_in ~= imin) emn_out = emn_in - step
}
else emn_out = 0
}

A.3 MAST Code for DC/DC Converter with SOC Energy Management
dcdc_emns.in

########################################################################
#### Buck DC/DC Converter Simplified Model
#### Model is intended for long term simulations
########################################################################
template dcdc_emns in out com emn = eta, vmax, vmin
electrical in, # converter input
    # converter input
out, # converter output
    # converter output
com # common terminal (usually grounded)
    # common terminal (usually grounded)
ref nu emn # where value comes in from ems

number eta=0.8, # converter efficiency (0 < eta < 1)
vmax=14.2, # maximum regulation voltage of converter
    # this is the no-load (open-circuit) voltage
vmin=13.8 # converter voltage at full load current
{
    # Branch current, voltage relationships
branch iin=i(in->com), vin=v(in,com)
branch iout=i(out->com), vout=v(out,com)
val nu vinl #
val nu voutl #
val nu ioutl #
val nu iin1

values {
    vinl = v(in) - v(com)
    voutl = v(out) - v(com)
    if (voutl >= 0.0 & vout1 < vmin) ioutl = emn
    else if (vout1 >= vmin & vout1 <= vmax) ioutl = emn -
        (emn/(vmax-vmin))*(voutl-vmin)
    else if (vout1 > vmax) ioutl = 0
    iin1 = vout1*iout1/(eta*vinl + lm)
}

equations {
    iout = - iout1 + vout/le6
    iin = iin1 - vin/le6
}
}
Appendix B

Battery Models

B.1 normalize_range.sin

The purpose of this template is to output the input value normalized between the two limit values hi_limit and lo_limit. The output value will range between 1 and zero.

```
template normalize_range in out = lo_limit, hi_limit

input nu in
var nu out
number lo_limit = undef, hi_limit = undef

{
    val nu outval, outval_eff

    values{
        outval = (in - lo_limit)/(hi_limit-lo_limit)
        if (outval <= 0) {
            outval_eff = 0
        }
        else if (outval >= 1) {
            outval_eff = 1
        }
        else{
            outval_eff = outval
        }
    }

    equations{
        out: out = outval_eff
    }
}
```

B.2 Battery with SOC Pin

batt_pb_1_w_soc.sin

This template, "batt_pb_1" models the typical electrical behavior of a SLA (automotive) lead-acid battery. The model is constructed to use a minimum of characterization parameters, namely: 1). Ampere*hour capacity, ("ahrated",required)
2). Nominal discharge current used to determine capacity, 
   ("inom", required)
3). Nominal open circuit voltage at full charge state, ("vnom", optional, default = 12.6 V)
4). Nominal internal resistance (dv/di) at full charge, ("rnom", optional, default = .3m Ohm)
5). Battery temperature, ("temp", optional, default = 27 C)
6). Number of cells, ("n_cell", optional, default = 6)
7). Initial state of charge, ("soc_init", optional, default = 1 (full charge))

The major effects modeled include:
1). Capacity limitation from depletion of active materials,
2). Variation of capacity with discharge current and 
   charge/discharge cycle history,
3). Cell gassing from overcharge,
4). Capacity "recovery" following high rate discharges,
5). Variation of capacity and voltage with battery temperature,
6). Self discharge,
7). Surface charge effects.

Consistant with a minimum number of characterization parameters, simplified scaling assumptions have been made to describe these effects.

Region of valid input arguements:
1). ahrated > 0
2). inom > 0
3). vnom > 0
4). rnom > 0
5). temp : unrestricted
6). 0 <= soc_init <= 1
7). n_cell should be a positive integer

Usage notes:
If soc_init is less than one, it is assumed that the battery reached this charge state by a discharge process from fully charged, and the battery has reached eletro-chemical equilibrium following the discharge (i.e. insignificant electrolyte concentration gradients.)
The user is allowed to set vnom at his pleasure to allow for minor variations of open circuit voltage with various acid concentrations.
# However, the number of cells and the nominal voltage must be related
# by \( v_{nom} = n_{cell} \times (2.1 + \epsilon) \), where \( \epsilon \ll 2.1 \).

encrypted template batt_pb_1_w_soc p m soc = ahrated, inom, vnom,
  soc_init, rnom, temp, n_cell

electrical p,m
ref nu soc

number vnom = 12.6, # Nominal open circuit voltage @ soc=100.
soc_init = 1, # Initial state-of-charge, given as a fraction.
  ahrated = undef, # Rated capacity, Amp*hours.
inom = undef, # Nominal current used to measure AmpHourrating
temp = 27, # Ambient temperature (degrees C).
rnom = .3m, # Nominal internal discharge resistance at SOC = 1
  n_cell = 6 # Number of battery cells

B.3 Battery Model with Sgmid (Specific Gravity) Pin

batt_pb_1_w_sgmid.sin

# This template, "batt_pb_1" models the typical electrical behavior of
# a lead-acid battery.
#
# The major effects modeled include:
# 1). Capacity limitation
# 2). Variation of available capacity with discharge rate and
# charge/discharge cycle history,
# 3). Cell gassing from high cell voltages,
# 4). "Float" current at full charge,
# 5). Capacity "recovery" following high rate discharges,
# 6). Variation of capacity and voltage with battery temperature,
# 7). Self discharge, (temperature dependent)
# 8). Surface charge effects.
#
# Consistant with a minimum number of characterization parameters,
# simplified scaling assumptions have been made to describe these
effects.
# The "typical" behavior of the battery is as outlined in _Handbook of
#
# Usage notes:
#
encrypted template batt_pb_1_w_sgmid p m sgmid = model, sg0, ratings, part_type, part_class
electrical p,m

struct {
    number ah_nom, # Nominal Amp-Hour capacity at tnom and inom
    inom, # Current (amps) used to determine ah_nom
    tend = 20, # Hours to end of discharge used to rate ah_nom
    rnom = 0, # Nominal "internal" electrical resistance
    n_cell = 6, # Number of battery cells
    sg_full = 1.265, # Specific gravity at full charge & 25 C
    sg_disc = 1.01, # Specific gravity at full discharge & 25 C
    tnom = 25, # Nominal temperature, C
    fah_tlow = 0.6, # Fraction of rated capacity available at tlow and inom
    fah_thi = 1.02, # Capacity factor at "high temperature" and inom
    tlow = -20, # Temperature (C) where fah_tlow is determined
    fc = 0.1, # Fraction of capacity "near" plate
    fah_max = 1.03, # Max capacity at "slow" discharge / ah_nom
    self_disc=0.25, # Percentage of ah_nom lost per day from self discharge at 25 C
    dtemp_sd = 16.37, # Temperature increase to get a factor of 2.72 (i.e. exp(1)) increase in self discharge
    i_flt = 2m, # Full charge "float" current (A/Ah), at v_flt V/cell
    v_flt = 2.3, # Cell voltage to give i_flt at "full charge"
    vthrs_gas = 2.39, # Threshold voltage (per cell) for onset of gassing, at 25 C
    dv_gas = .2, # Sets exponential scaling of gassing current with terminal voltage
    tc_v = 0.15m, # Temperature coefficient of open circuit volts/cell
    tc_r = 7.5m, # Temperature coefficient of internal resistance at full charge
    sgc_r = 0.5 # Fractional change in internal resistance
}
between full charge and full discharge

}` model=()

number sg0 = 1.265 # Initial specific gravity

external number temp, include_stress

struc {
  number v_max, # Maximum differential terminal voltage, v(p) - v(m)
  v_min, # Minimum differential terminal voltage, v(p) - v(m)
  v_nom, # Nominal differential terminal voltage; Used to determine "Low voltage" stress ratio
  i_chg_max, # Maximum terminal current on charge, positive i(p->m)
  i_dchg_max # Maximum terminal current on discharge, positive i(m->p)
} ratings=()

string part_type = "battery",
  part_class= "lead acid flooded"

export val v v_diff_term # Differential terminal voltage
export val i i_charge # Current entering terminal p

{
  val v v_under_vnom, # ratings->v_nom - v_diff_term; Used to compute "Min voltage" stress ratio
  v_perccell # Volts per cell, v_diff_term/n_cell

  val i i_gas, # "Gassing" current, i.e. current from overvoltage charging
  i_self_disc, # "Self discharge" current, i.e. loss of

  capacity # not drawn from terminals
  i_echem # Current involved in battery electro-

  chemical action # i(p) = i_echem + i_float + i_gas + i_self_disc
  !crypt_start
Appendix C

Simulation and Test Profiles

C.1 Idle Profile

*Idle.scs*

```plaintext
# Loadcycle: idle.scs
# Conditions: hot, raining, night-time
#
#
# posseq = position sequence for related switch
# Format: [(t1, pos1), (t2, pos2)]
#
# Load off = Switch open = position 1
# Load on = Switch closed = position 2
#
# For loads with 3 settings:
# Load off = position 1
# Low = position 2
# Medium = position 3
# High = position 4
#
#
# DC/DC Converter
# Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (14,2)]

# Loads on 42V bus
# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (14,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6 W, 5.97 A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (14,2)]

# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (14,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (12,2), (14,1)]

# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1)]

# Heated Windshield: Resistance, 700 W, 16.67 A
```

81
# Heated Rear Window: Resistance, 280W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (16,2)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (20,2)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245 W, 5.83 A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1), (33,2)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter /sdr_prsq.sdr_windows/posseq = [(0,1)]

### Future 42V Loads, added individually, default switch position is open

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
alter /sdr_prsq.sdr_ac_compressor/posseq = [(0,1)]

# Rear Seat Heaters: Resistance w/ Settings, 180 W, 4.29 A
alter /sdr_prsq.sdr_rear_seat_htrs/posseq = [(0,1)]

# All Weather Night Vision: Current, 100 W, 2.38 A
alter /sdr_prsq.sdr_night_vision/posseq = [(0,1)]

# Active Suspension: Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_act_suspension/posseq = [(0,1)]

# Active Engine Mount: Resistance 70 W, 1.67 A
alter /sdr_prsq.sdr_act_eng_mount/posseq = [(0,1)]

# Water Pump: Resistance, 300 W, 7.14 A
alter /sdr_prsq.sdr_water_pump/posseq = [(0,1)]

# Electromagnetic Valve Engine (8 cylinder):
# Speed-Dependent Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_electromag_valve_eng/posseq = [(0,1), (14,2)]

# Loads on 14V bus
# Total Overall for Duration:

# Base Loads: Resistance, 187.8 W, 13.41 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_14V/posseq = [(0,1), (14,2)]
# Speed-Dependent Base Loads: Speed-Dependent Resistance, 68.78 W, 4.91 A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_14V/posseq = [(0,1), (14,2)]

# High Beam Headlamps: Resistance, 130 W, 9.29 A
alter /sdr_prsq.sdr_highbeams/posseq = [(0,1)]

# Turn Lights: Resistance, 110.8 W, 7.91 A
alter /sdr_prsq.sdr_turn/posseq = [(0,1)]

# All Brake Related Loads: Resistance, 470.6 W, 33.61 A
alter /sdr_prsq.sdr_brakes/posseq = [(0,1)]

# Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors/posseq = [(0,1)]

# Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone/posseq = [(0,1)]

# CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd/posseq = [(0,1), (20,2)]

# Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_navaid/posseq = [(0,1)]

# Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise/posseq = [(0,1)]

# Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate/posseq = [(0,1), (45,2)]

# Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna/posseq = [(0,1), (20,2), (24,1)]

# Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump/posseq = [(0,1)]

# ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
alter /sdr_prsq.sdr_abs_tc/posseq = [(0,1)]

### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]
alter /sdr_prsq.sdr_alarm/posseq = [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams/posseq = [(0,1)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_lights/posseq = [(0,1), (11,2)]

# Power Door Locks: Power, 248 W, 17.7 A
alter /sdr_prsq.sdr_locks/posseq = [(0,1), (1,2), (2,1), (8,2), (9,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
C.2 High Speed Profile

**summer_worst_const.scss**

```
# DC/DC Converter
# Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (28,2)]

# Loads on 42V bus
# Total Overall for Duration:

# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6 W, 5.97 A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (28,2)]
```
# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (28,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (26,2), (28,1)]

# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1)]

# Heated Windshield: Resistance, 700 W, 16.67 A
alter /sdr_prsq.sdr_windshield/posseq = [(0,1)]

# Heated Rear Window: Resistance, 280 W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (330,4), (750,3)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (37,2)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245 W, 5.83 A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1), (30,4), (930,3)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter /sdr_prsq.sdr_windows/posseq = [(0,1), (32,2), (36,1), (332,2), (336,1)]

### Future 42V Loads, added individually, default switch position is open

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
alter /sdr_prsq.sdr_ac_compressor/posseq = [(0,1)]

# Rear Seat Heaters: Resistance w/ Settings, 180 W, 4.29 A
alter /sdr_prsq.sdr_rear_seat_htrs/posseq = [(0,1)]

# All Weather Night Vision: Current, 100 W, 2.38 A
alter /sdr_prsq.sdr_night_vision/posseq = [(0,1), (40,2)]

# Active Suspension: Resistance, 1000 W, 23.81 A
alter /sdr_prsq.sdr_act_suspension/posseq = [(0,1)]

# Active Engine Mount: Resistance 70 W, 1.67 A
alter /sdr_prsq.sdr_act_eng_mount/posseq = [(0,1)]

# Water Pump: Resistance, 300 W, 7.14 A
alter /sdr_prsq.sdr_water_pump/posseq = [(0,1)]
Heated Catalytic Converter, 3000 W, 71.43 A
alter /sdr_prsq.sdr_catalytic/posseq = [(0,1), (28,2), (53,1)]

Electromagnetic Valve Engine (8 cylinder):
# Speed-Dependent Resistance, 1000 W, 23.81 A
# Always on when engine is on!
alter /sdr_prsq.sdr_electromag_valve_eng/posseq = [(0,1), (28,2)]

# Loads on 14V bus
# Total Overall for Duration:

Base Loads: Resistance, 187.8 W, 13.41 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_14V/posseq = [(0,1), (28,2)]

Speed-Dependent Base Loads: Speed-Dependent Resistance, 68.78 W, 4.91 A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_14V/posseq = [(0,1), (28,2)]

High Beam Headlamps: Resistance, 130 W, 9.29 A
alter /sdr_prsq.sdr_highbeams/posseq = [(0,1)]

Turn Lights: Resistance, 110.8 W, 7.91 A
alter /sdr_prsq.sdr_turn/posseq = [(0,1)]

All Brake Related Loads: Resistance, 470.6 W, 33.61 A
alter /sdr_prsq.sdr_brakes/posseq = [(0,1)]

Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors/posseq = [(0,1)]

Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone/posseq = [(0,1)]

CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd/posseq = [(0,1), (37,2)]

Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_navaid/posseq = [(0,1), (42,2)]

Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise/posseq = [(0,1), (120,2)]

Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate/posseq = [(0,1), (1000,2)]

Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna/posseq = [(0,1), (37,2), (40,1)]

Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump/posseq = [(0,1)]

ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
alter /sdr_prsq.sdr_abs_tc/posseq = [(0,1)]
### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]
# alter /sdr_prsq.sdr_alarm/posseq = [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams/posseq = [(0,1), (25,2)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_lights/posseq = [(0,1)]

# Power Door Locks: Power, 248 W, 17.7 A
alter /sdr_prsq.sdr_locks/posseq = [(0,1), (11,2), (12,1), (22,2), (23,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
alter /sdr_prsq.sdr_trunk_open/posseq = [(0,1), (1,2), (2,1)]

# Trunk Compartment Lamp: Resistance, 10 W, .71 A
alter /sdr_prsq.sdr_trunk_lamp/posseq = [(0,1), (2,2), (10,1)]

# Power Trunk Pull-down: Power, 22 W, 1.57 A
alter /sdr_prsq.sdr_trunk_close/posseq = [(0,1), (10,2), (13,1)]

# Driver Door Open: Resistance, 27 W, 1.93 A
alter /sdr_prsq.sdr_driver/posseq = [(0,1), (13,2), (16,1)]

# Seat Adjustments: Power, 73 W, 5.21 A
alter /sdr_prsq.sdr_seat_adjust/posseq = [(0,1), (17,2), (20,1)]

### C.3 City Profile

**winter_worst_ece15.scs**

```plaintext
### Loadcycle: winter_worst_ece15.scs
### Conditions: cold, snow, night-time,
### Customized for ece15_city.dat
### posseq = position sequence for related switch
### Format: [(t1, pos1), (t2, pos2)]
### Load off = Switch open = position 1
### Load on = Switch closed = position 2
### For loads with 3 settings:
### Load off = position 1
### Low = position 2
### Medium = position 3
### High = position 4
### Note: Time ends at 2515.
```

# DC/DC Converter
Always on when engine is on
alter /sdr_prsq.sdr_converter/posseq = [(0,1), (28,2)]

# Loads on 42V bus
# Total Overall for Duration:

# Base Loads: Resistance, 92 W, 2.19 A
# Always on when engine is on
alter /sdr_prsq.sdr_base_loads_42V/posseq = [(0,1), (28,2)]

# Speed-Dependent Base Loads: Speed-Dependent Resistance, 250.6 W, 5.97 A
# Always on when engine is on
alter /sdr_prsq.sdr_speed_loads_42V/posseq = [(0,1), (28,2)]

# Emissions Air Pump: Power, 150 W, 3.57 A
# Always on when engine is on
alter /sdr_prsq.sdr_emissions/posseq = [(0,1), (28,2)]

# Starter: Power, 3150 W, 75 A
alter /sdr_prsq.sdr_starter/posseq = [(0,1), (26,2), (28,1)]

# Seat Heaters: Resistance, 220 W, 5.24 A
alter /sdr_prsq.sdr_seat_htrs/posseq = [(0,1), (33)]

# Heated Windshield: Resistance, 700 W, 16.67 A
alter /sdr_prsq.sdr_windshield/posseq = [(0,1), (32), (332)]

# Heated Rear Window: Resistance, 280 W, 6.67 A
alter /sdr_prsq.sdr_defog/posseq = [(0,1), (31), (631)]

# Windshield Wipers, Front: Current w/ Settings, 30 W, .71 A
alter /sdr_prsq.sdr_wipers/posseq = [(0,1), (35), (300), (480), (750)]

# Radio/Subwoofer: Power, 40 W, .95 A
alter /sdr_prsq.sdr_radio/posseq = [(0,1), (37)]

# Heater: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_heater/posseq = [(0,1), (30), (930)]

# All Air Conditioning Related Loads: Resistance w/ Settings, 245 W, 5.83 A
alter /sdr_prsq.sdr_air_cond/posseq = [(0,1)]

# Vent: Resistance w/ Settings, 195 W, 4.64 A
alter /sdr_prsq.sdr_ps_cmp_blwr/posseq = [(0,1)]

# Sun Roof: Power, 190 W, 4.52 A
alter /sdr_prsq.sdr_sunroof/posseq = [(0,1)]

# Power Windows: Power, 270 W, 6.43 A
alter /sdr_prsq.sdr_windows/posseq = [(0,1)]

### Future 42V Loads, added individually, default switch position is open

# A/C Compressor Pump: Power w/ Settings, 3000 W, 71.43 A
Brakes sequence continued in winter_worst_ece15EXT1.scs

# Power Mirror Heaters: Resistance, 30 W, 2.14 A
alter /sdr_prsq.sdr_mirrors,posseq = [(0,1)]

# Telephone: Current, 5 W, .36 A
alter /sdr_prsq.sdr_phone,posseq = [(0,1)]

# CD Changer: Current, 13 W, .93 A
alter /sdr_prsq.sdr_cd,posseq = [(0,1), (37,2)]

# Navigation Aid: Current, 50 W, 3.57 A
alter /sdr_prsq.sdr_navaid,posseq = [(0,1), (42,2)]

# Cruise Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_cruise,posseq = [(0,1)]

# Automatic Climate Control: Current, 25 W, 1.79 A
alter /sdr_prsq.sdr_climate,posseq = [(0,1), (45,2)]

# Antenna Lift: Power, 45 W, 3.21 A
# On when radio turns on
alter /sdr_prsq.sdr_antenna,posseq = [(0,1), (37,2), (40,1)]

# Automatic Tire Pump: Power, 100 W, 7.14 A
alter /sdr_prsq.sdr_tire_pump,posseq = [(0,1)]

# ABS/TC (Anti-Lock Brake System & Traction Control) Related Loads:
# Power, 324 W, 23.14 A
# 12/29/98 -- Assume to be on when brakes are on
alter /sdr_prsq.sdr_abs_tc,posseq = [(0,1)]

### Key-off Loads (Can be on even when ignition is off)

# Anti-Theft Warning Device: Current, .2 W, .014 A
# Always on: switch driver set to [(0,2)]
alter /sdr_prsq.sdr_alarm,posseq = [(0,2)]

# All Parking Lights and Lowbeams: Resistance, 204.2 W, 14.59 A
alter /sdr_prsq.sdr_parking_and_lowbeams,posseq = [(0,1), (25,2)]

# All Parking Lights: Resistance, 94.2 W, 6.73 A
alter /sdr_prsq.sdr_parking_light,posseq = [(0,1)]

# Power Door Locks: Power, 248 W, 17.7 A
alter /sdr_prsq.sdr_locks,posseq = [(0,1), (11,2), (12,1), (22,2), (23,1)]

# Power Trunk Opener: Power, 242 W, 17.29 A
alter /sdr_prsq.sdr_trunk_open,posseq = [(0,1), (1,2), (2,1)]

# Trunk Compartment Lamp: Resistance, 10 W, .71 A
alter /sdr_prsq.sdr_trunk_lamp,posseq = [(0,1), (2,2), (10,1)]
# Power Trunk Pull-down: Power, 22 W, 1.57 A
alter /sdr_prsq.sdr_trunk_close/posseq = [(0,1), (10,2), (13,1)]

# Driver Door Open: Resistance, 27 W, 1.93 A
alter /sdr_prsq.sdr_driver/posseq = [(0,1), (13,2), (16,1)]

# Seat Adjustments: Power, 73 W, 5.21 A
alter /sdr_prsq.sdr_seat_adjust/posseq = [(0,1), (17,2), (20,1)]
Appendix D

State of Charge Energy Management System in Breadboard

D.1 State of Charge Calculation in LabView

soc.c

/*
 * CIN source file for state of charge calculation
 */

#include "extcode.h"

CIN MgErr CINRun(float64*_36vBatteryCurrentChart, float64* _12vBatteryCurrentChart, float32*_42vSOC, float32 * _14vSOC);

CIN MgErr CINRun(float64*_36vBatteryCurrentChart, float64* _12vBatteryCurrentChart, float32*_42vSOC, float32 * _14vSOC) {

    * _42vSOC = (*_42vSOC + (*_36vBatteryCurrentChart / 3600));
    * _14vSOC = (*_14vSOC + (*_12vBatteryCurrentChart / 3600));

    return noErr;
}

D.2 State of Charge Energy Management in LabView

ems.c

/*
 * CIN source file ems.c
 */

#include "extcode.h"

/* ENTER YOUR CODE HERE */

CIN MgErr CINRun(float32*_42v_SOC, float32*_14v_SOC, uInt8*DC_DC_Converter_State);

CIN MgErr CINRun(float32*_42v_SOC, float32*_14v_SOC, uInt8*DC_DC_Converter_State) {

    /*
    * _42v_SOC = (*_42v_SOC + (*_36v_Battery_Current_Chart / 3600));
    * _14v_SOC = (*_14v_SOC + (*_12v_Battery_Current_Chart / 3600));
    */
    if (*_14v_SOC >= 1.15)
        *DC_DC_Converter_State = 0;

else if (*_14v_SOC >= 1.05 && _14v_SOC < 1.15)
    *DC_DC_Converter_State = 0;
else if (*_14v_SOC >= .90 && *_14v_SOC < 1.05) {
    if (*_42v_SOC >= 1.05)
        *DC_DC_Converter_State = 255;
    else if (*_42v_SOC >= .90 && *_42v_SOC < 1.05)
        *DC_DC_Converter_State = *DC_DC_Converter_State;
    else if (*_42v_SOC >= .5 && *_42v_SOC < .90) [ 
        if (*DC_DC_Converter_State != 0)
            *DC_DC_Converter_State = *DC_DC_Converter_State - 1;]
    else
        *DC_DC_Converter_State = 0; }
else if (*_14v_SOC >= .5 && *_14v_SOC < .90) {
    if (*_42v_SOC >= 1.05)
        *DC_DC_Converter_State = 255;
    else if (*_42v_SOC >= .90 && *_42v_SOC < 1.05) { 
        if (*DC_DC_Converter_State != 255)
            *DC_DC_Converter_State = *DC_DC_Converter_State + 1; }
    else if (*_42v_SOC >= .5 && *_42v_SOC < .90) { 
        if (*DC_DC_Converter_State != 0)
            *DC_DC_Converter_State = *DC_DC_Converter_State - 1; }
    else
        *DC_DC_Converter_State = 0; }
else {
    if (*_42v_SOC >= .9) {
        if (*DC_DC_Converter_State != 255)
            *DC_DC_Converter_State = *DC_DC_Converter_State + 1; }
    else if (*_42v_SOC >= .5 && *_42v_SOC < .90) { 
        if (*DC_DC_Converter_State != 0)
            *DC_DC_Converter_State = *DC_DC_Converter_State - 1; }
    else
        *DC_DC_Converter_State = 0; }
return noErr;