DC-to-DC Buck Converter

By

Kyle Christopher Roman

SENIOR PROJECT
ELECTRICAL ENGINEERING DEPARTMENT
CALIFORNIA POLYTECHNIC STATE UNIVERSITY

San Luis Obispo

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Abstract

The growth of sustainable energy requires many components to work in harmony creating one efficient and effective system. Sustainable energy generation that produces a DC current varying in voltage requires a subsystem to convert voltage to a practical and usable value. The DC to DC Buck converter converts high DC solar generated voltage to a 12V output. This Modular-Level power electronic (MLPE) device performs as a solar charge controller for small lithium ion batteries. Fluctuating voltage levels generated by Photovoltaic cells makes the solar controller a critical part of the solar system. Regulating the DC voltage allows safe and effective battery changing. The converter uses Pulse Width Modulation (PWM) to improve efficiency and longevity of the battery system [8]. The DC to DC converter receives 12V to 40V at a maximum of 1 amperes typical of portable solar applications. The step-down converter designed at the transistor and integrated circuit level uses PWM supplying constant voltage [3]. PWM controls switches (transistors) that enables or disables current flow via digital signals to control the step-down process. Inductors enable energy conservation in the circuit during on/off cycles. The size of the inductor determines the effectiveness and efficiency. The converter’s battery charging responsibility contains the most important performance criteria. Designed for charging lithium ion 18650 cells, this converter connects to compatible lithium ion charging stations. Development of the buck converter focuses on efficiency, magnetic design and voltage regulation. The project focuses less on charging cycles for the cells that charging docks handle.
Introduction:

In the last twenty years, the generation of energy focuses more on sustainability than convenience. Burning fossil fuels and coal creates carbon emissions that harm the planet. Maintaining energy needs and limiting the impacts on the earth, one alternative relies on the sun to convert electromagnetic radiation to electric energy through the photovoltaic effect. Tiny cells manufactured and assembled in arrays to create solar panels allow energy generation throughout many places. Like any modern energy generation, converting sunlight to electric energy requires efficiency, effectiveness, and compatibility among current grid system and electrical components. One critical process among solar systems, involves converting high voltage power to low voltage power. The Solar Controller executes this process using a buck converter.

The growth of photovoltaic energy leads engineers into improving and redesigning MLPE that serve as a critical part in the energy system. MLPE allows the operation of photovoltaic modules to operate in the maximum power point (MPP), therefore making the most efficient energy conversion. Many papers have debated the best methods of design and implementation of MLPE in PV applications. *High-Performance Quasi-Z-Source Series Resonant DC-DC Converter for Photovoltaic Module-Level Power Electronics Applications* focuses on full-power converter for the parallel connection of PV modules [2]. This approach requires each PV panel to equip a microconverter that ties its outputs to a central dc bus of the PV power system. The microconverter operates as a self-powered high-efficiency step-up dc-dc converter with galvanic isolation. Operating autonomously, this topology tracks the maximum power point locally at each PV panel. This device also operates in “Buck Mode” when the input voltage is higher than required output. This mode controls output by phase shift modulation (PSM) at the resonant frequency.

This paper serves as the preparation for design of a DC-DC Buck Converter. Chapter 1 introduces the MLPE in PV application while refereeing to current topologies. Chapter 2 provides the customer needs assessment, requirements and specifications, and deliverables throughout the design process. This section provides tables to link marketing requirements to design specifications. Chapter 3 shows the Level 0 and Level 1 block diagrams along with their functional tables of the converter. Chapter 4 focuses on the Gantt charts for Winter 2017, Spring 2017, Summer 2107, and Fall 2017. This section provides a narrative describing the deliverable, milestones and achievements throughout the design process on a time basis. Next, Chapter 5 researches power electronics theory, and calculates important values such as critical inductance and duty cycle. Chapter 6 researches battery charging techniques for lithium ion cells. The section explains how charging stages affect quality and performance of the cell. Chapter 7 focuses on the design process of the buck converter circuit. Two design iteration with different IC compare size, power, and complexity. After comparison, parts of chosen design are ordered and explanation into the value explained. This chapter also includes the stress sheet analysis and pictures of the complete circuit. Chapter 8 includes test data on the assembled buck converter. Chapter 9 provides a literature and citations that enables quality information and research. Finally, Appendix D includes the ABET senior project analysis of the DC-DC Buck Converter.
Chapter 2 includes the Customer Needs Assessment, Requirements and Specifications, and a table to highlight key points. Table II provides dated deliverable throughout the design process. These items give meaning and structure to the project while creating a well thought out design. The next chapter explains the system’s functional decomposition.

Customer Needs Assessment

Customers of the DC to DC step down converter need a small portable device that takes in high DC voltages from a solar panel and steps down the voltage to 12 V for charging a battery system. Customers range from home owner, business owners, solar companies, and solar system enthusiast. To elicit the needs of potential customer, communication between the customer and developer is critical. First, Amazon and Google reviews on current DC-DC solar module controllers were read. Next, the National Electrical Code (NEC) for photovoltaic systems was implemented into the design. Lastly, specifications of current solar controllers, such as MornigStar, were reviewed. The customer needs the device portable, safe, intuitive and reliable. Customers’ needs a display on the device to show on/off state, input and output power, and load tracking. Customers need the device to operate in various weather conditions, elevations, and temperatures. Finally, the customer needs the device to operate in a voltage range of 14V – 40V with an output current up to 1.5A.

Requirements and Specifications

Table I shows engineering specification, justification for specifications, and relationship to marketing requirements. The DC-DC Buck converter meets NEC requirements for photovoltaic systems and meets standards for small scale applications [12]. First, 10-gauge wire defines the standard for PV applications for connectivity between PV panels and modules. Next, the location of the device’s implementation justifies an operational temperature -20°C ~ 60°C and weather resistance of IP 33. Next, charging a battery in a moderate time frame requires a DC current around 1A. Input voltages for small scale solar application include 14V – 40V [8]. Transistors, integrated circuit, and inductors limit the voltage levels and efficiency in power electronics. Moreover, the device provides safe operation by the customer through reverse connection, temperature, overload, and short circuit protection. The device needs power for the LCD screen and control system. Lastly, the device must travel well and not take up major space. This requires the device’s dimensions to not exceed (7 x 4 x 2)".
TABLE I
DC TO DC STEP-DOWN CONVERTER SPECIFICATIONS

<table>
<thead>
<tr>
<th>Marketing Requirements</th>
<th>Engineering Specifications</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operational Temperature: -20°C ~ 60°C</td>
<td>Converter connected outdoors.</td>
</tr>
<tr>
<td>1</td>
<td>Weather resistance: IP 33</td>
<td>Resistant against dripping and sprayed water.</td>
</tr>
<tr>
<td>1,4,6</td>
<td>Max charge/discharge current: 1.5A</td>
<td>Lithium Ion Cells: 18650</td>
</tr>
<tr>
<td>2,4</td>
<td>Devices intuitively describes operation instruction.</td>
<td>Intuitive operation.</td>
</tr>
<tr>
<td>1,5</td>
<td>Input voltage levels: 14V – 40V</td>
<td>Typical voltage range of small scale solar systems.</td>
</tr>
<tr>
<td>3</td>
<td>Device must not exceed (7 x 4 x 2)” dimension size.</td>
<td>Comparable among other solar controllers.</td>
</tr>
<tr>
<td>2,5</td>
<td>Device displays: Input/output voltage, charging current, On/Off status.</td>
<td>Device displays information for quality control and user experience.</td>
</tr>
<tr>
<td>4,1</td>
<td>Reverse connection, temperature, overload, and short circuit protection.</td>
<td>Users and device protected against dangerous currents and overheating.</td>
</tr>
<tr>
<td>1,4</td>
<td>10 Gauge Wire connectors</td>
<td>NEC standard [12]</td>
</tr>
<tr>
<td>6</td>
<td>PWM enables constant voltage delivery.</td>
<td>Most Effective constant charging capability</td>
</tr>
<tr>
<td>6</td>
<td>Marine rated terminals/anodized case</td>
<td>Protective and durable case.</td>
</tr>
</tbody>
</table>

Marketing Requirements
1. Reliable.
2. Convenient and intuitive
3. Portable.
4. Safe operation.
5. Display
6. Efficient and Effective

TABLE II
DC TO DC CONVERTER DELIVERABLES

<table>
<thead>
<tr>
<th>Delivery Date</th>
<th>Deliverable Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/22/17</td>
<td>Design Review</td>
</tr>
<tr>
<td>4/20/17</td>
<td>LTSpice schematic</td>
</tr>
<tr>
<td>5/4/17</td>
<td>EE 461 demo</td>
</tr>
<tr>
<td>5/7/17</td>
<td>EE 461 report</td>
</tr>
<tr>
<td>10/7/17</td>
<td>EE 462 demo</td>
</tr>
<tr>
<td>10/30/17</td>
<td>ABET Sr. Project Analysis</td>
</tr>
<tr>
<td>11/6/17</td>
<td>Sr. Project Expo Poster</td>
</tr>
<tr>
<td>12/5/17</td>
<td>EE 462 Report</td>
</tr>
</tbody>
</table>
Chapter 3 provides the Level 0 and Level 1 block diagrams, along with their function tables, for the DC to DC Buck Converter. This chapter shows a visual representation of input and output requirements, internal functionality, and external connection. Tables show the description and functionality of each item in the block diagrams. Figure 1 shows the Level 0 block diagram of the DC to DC Buck Converter which simply show input and output requirements. The DC voltage between 14V and 40V generated by the PV panel feeds through the Buck Converter that supplies 12V and 1.5A maximum. Figure 2 shows the Level 1 block diagram bring forth functional subcomponents of the converter and external system. The buck converter filters the input voltage received by a solar panel through capacitors. Next, the filtered input stage sends current to the inductor that stores energy by control of the PWM of the IC and supplies power to the IC. During the output stage, capacitors filter the voltage to produce an allowable ripple voltage. The output also sends voltage to a resistor divider feedback that connects to a comparator within the IC. Lastly, the battery charging system receives the output power and controls the charging of the cells. Table III provides the description and functionality of the Level 0 Block Diagram in Figure 1. Table IV provides the description and functionality of each stage internal and external to the Buck Converter seen in Figure 1. In the next chapter, Gantt Charts show milestone completion expectations and project cost analysis.

**Figure 1: Level 0 Block Diagram**

-Chapter 3-
Figure 2: Level 1 Block Diagram

**TABLE III**
DC TO DC CONVERTER FUNCTION TABLE 0

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>High Voltage 14V – 40V @ 1A max current</td>
<td>Solar Panel’s generated power</td>
</tr>
<tr>
<td>Output</td>
<td>12V DC Power @ 1.5A maximum current</td>
<td>Charge battery or power appliances</td>
</tr>
<tr>
<td>System</td>
<td>Solar Cells connected DC to DC Buck Converter</td>
<td>Converts Sunlight to a 12V DC current.</td>
</tr>
</tbody>
</table>

**TABLE IV**
DC TO DC CONVERTER FUNCTION TABLE 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Sunlight-Electromagnetic Radiation</td>
<td>Energy</td>
</tr>
<tr>
<td>Input</td>
<td>High Voltage 14V – 40V @ 1A max current</td>
<td>Solar Panel’s generated power</td>
</tr>
<tr>
<td>Output</td>
<td>12V DC Power @ 1.5A maximum current</td>
<td>Charge battery or power appliances</td>
</tr>
<tr>
<td>System</td>
<td>Input Stage Filtering</td>
<td>Filters input voltage with capacitors</td>
</tr>
<tr>
<td>System</td>
<td>IC Pulse Width Modulator</td>
<td>Controls PWM and switching</td>
</tr>
<tr>
<td>System</td>
<td>Step-Down Stage</td>
<td>Steps down voltage by energy storage</td>
</tr>
<tr>
<td>System</td>
<td>Output Stage</td>
<td>Filters output voltage</td>
</tr>
<tr>
<td>System</td>
<td>Battering Charging System</td>
<td>Controls charging of Lithium Ion Batteries</td>
</tr>
</tbody>
</table>
Gantt Chart & Cost Estimates

Chapter 4 includes a detailed planning structure of the Buck Converter by date and milestones while estimating the cost of the entire project. Developing the DC to DC Buck converter calls for a well thought out plan that guides the process. Gantt provide structure towards completion of certain components and sub components while reporting milestones. Figure 3 shows the Gantt chart for the preparation of the DC to DC Buck Converter for Winter 2017 quarter. The preparation involves writing the abstract, introduction, block diagrams, literature search, cost estimates, ABET Sr. project analysis, requirements and specifications, and narratives to each section. The preparation stage seen in figure 3 takes 10 weeks for completion. Figure 4 provides the eleven-week Gantt Chart for second stage of developing the converter in Spring 2017. This stage involves research, part shipping, two design iterations, testing, coding, and documentation. Next, the third stage in the development process occurs during the summer of 2017. Figure 5 provides the four-month Gantt Chart involving catch up, research, revising design iterations, testing and documentation. Finally, figure 6 provides the 10-month Gantt chart for the last stage in the developing the DC to DC Buck Converter in Fall 2017. This stage involves the design for the casing around the converter the device assembly and final testing of the product. Table V provides a cost estimate for materials, components, and labor. The cost estimates include the labor involved for anything in the design process. Estimates for components provide expectations while Table VII represents the final bill of materials (BOM) and labor costs. In the next chapter the theory behind power electronics explains derivations, typologies, and component decisions.

![Figure 3: Winter 2017 Quarter Gantt Chart](image-url)
### TABLE V
DC TO DC CONVERTER COST ESTIMATES

<table>
<thead>
<tr>
<th>Cost Estimates (All prices in Dollars)</th>
<th>Least Cost</th>
<th>Medium Cost</th>
<th>Highest Cost</th>
<th>Total Adjusted Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadboard and Parts</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>Discrete Parts + Chips</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Soldering</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>PCB</td>
<td>30</td>
<td>40</td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td>Casing</td>
<td>80</td>
<td>100</td>
<td>150</td>
<td>105</td>
</tr>
<tr>
<td>Casing Parts</td>
<td>30</td>
<td>50</td>
<td>50</td>
<td>47</td>
</tr>
<tr>
<td>Overhead</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Labor @ $26/hr (100/150/250)hrs</td>
<td>2600</td>
<td>3900</td>
<td>6500</td>
<td>4116.67</td>
</tr>
<tr>
<td>Total</td>
<td>243.72</td>
<td></td>
<td></td>
<td>4418.33</td>
</tr>
</tbody>
</table>

### TABLE VI
PROJECT BILL OF MATERIALS & LABOR COSTS

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Distributor</th>
<th>Part #</th>
<th>Unit Price</th>
<th>Quantity</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWA</td>
<td>Mouser</td>
<td></td>
<td>62.50</td>
<td>1</td>
<td>62.50</td>
</tr>
<tr>
<td>Ceramic Cap (1000pF)</td>
<td>Mouser</td>
<td>A102J15C0GF5TAA</td>
<td>0.33</td>
<td>2</td>
<td>0.66</td>
</tr>
<tr>
<td>Schottky Diode</td>
<td>Mouser</td>
<td>1N5819-T</td>
<td>0.34</td>
<td>2</td>
<td>0.68</td>
</tr>
<tr>
<td>Schottky Diode</td>
<td>Mouser</td>
<td>SB240-E3/54</td>
<td>0.46</td>
<td>2</td>
<td>0.92</td>
</tr>
<tr>
<td>Switching Reg.</td>
<td>Mouser</td>
<td>MC34063AP</td>
<td>0.60</td>
<td>5</td>
<td>3.00</td>
</tr>
<tr>
<td>Inductor</td>
<td>Mouser</td>
<td>WE-221</td>
<td>1.10</td>
<td>1</td>
<td>1.10</td>
</tr>
<tr>
<td>Lithium Ion 18650 Cells (4)</td>
<td>Mouser</td>
<td></td>
<td>8.99</td>
<td>1</td>
<td>8.99</td>
</tr>
<tr>
<td>Lithium Ion Charge Controller</td>
<td>Mouser</td>
<td></td>
<td>49.99</td>
<td>1</td>
<td>49.99</td>
</tr>
<tr>
<td>Resistor 10k</td>
<td>Mouser</td>
<td></td>
<td>0.10</td>
<td>2</td>
<td>0.20</td>
</tr>
<tr>
<td>Resistor 1.2k</td>
<td>Mouser</td>
<td></td>
<td>0.10</td>
<td>2</td>
<td>0.20</td>
</tr>
<tr>
<td>Resistor 0.4</td>
<td>Mouser</td>
<td></td>
<td>0.40</td>
<td>2</td>
<td>0.80</td>
</tr>
<tr>
<td>Resistor 20k</td>
<td>Mouser</td>
<td></td>
<td>0.10</td>
<td>2</td>
<td>0.20</td>
</tr>
<tr>
<td>Polar Caps</td>
<td>Mouser</td>
<td>Assortment</td>
<td>0.60</td>
<td>20</td>
<td>12.00</td>
</tr>
<tr>
<td>Test Equipment</td>
<td>RadioShack</td>
<td></td>
<td>30.00</td>
<td>1</td>
<td>30.00</td>
</tr>
<tr>
<td>Development Board/Connectors</td>
<td>RadioShack</td>
<td></td>
<td>29.99</td>
<td>1</td>
<td>29.99</td>
</tr>
<tr>
<td>Resistor 0.39</td>
<td>RadioShack</td>
<td></td>
<td>1.50</td>
<td>1</td>
<td>1.50</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>SUNPower</td>
<td>SP-10W18V</td>
<td>40.99</td>
<td>1</td>
<td>40.99</td>
</tr>
<tr>
<td>BOM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>243.72</td>
</tr>
<tr>
<td>Hourly Wage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td></td>
<td></td>
<td>27.00</td>
<td>180</td>
<td>4860.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5347.44</td>
</tr>
</tbody>
</table>
Chapter 5 provide theory of power electronics while exploring typologies of converters and deriving certain equations that calculate important values used. This chapter reviews derivations: critical inductance, transfer function, and duty cycle. In power electronics, voltage regulation relies on the storage of energy in the magnetic field of an inductor. To control the discharge of this energy a field effect transistor (FET) switches on and off to enable current flow through the inductor. Figure 7 displays a simple buck converter typology that uses an inductor to store energy, transistor “Vswitch” to charge the inductor with Vin supply, a diode to enable discharge of the inductor during off cycles, and a filtering capacitor. Buck converters contain other typologies that use various arrangements of transistors and energy storing techniques. This basic buck controller focusing on the basic typology for size and simplicity. In a buck controller, the duty cycle of the switching frequency determines the step-down voltage. An integrated circuit controls switching frequency and duty cycle. Components in a power electronic device must meet certain rating and power needs. In power electronics, the require input voltage range, output voltage, and load current depends on the design of the inductor. The inductor must not saturate with any current it receives but also should use most of its energy storing capabilities. The next chapter researches lithium ion battery charging cycles.

**Figure 7: Simple Buck Converter**

**Critical Inductance:**

To calculate critical inductance the boundary conduction mode (BCM) of the inductor is used. The voltage across the inductor during ON or OFF switching.

\[
v_L = L \frac{di_L}{dt} \rightarrow di_L = \frac{v_L}{L} dt \rightarrow \Delta i_L = \frac{v_L}{L} \Delta t
\]

\[
2I_L = \frac{v_L}{L} \Delta t \rightarrow L = \frac{v_L}{2I_L} \Delta t \rightarrow L_c = \frac{v_L}{2I_L} \Delta t
\]
\[ L_C = \frac{v_L}{2I_L} \Delta t = \frac{v_{LON}}{2I_L} t_{ON} = \frac{v_{LON}}{2I_L} DT_s = \frac{v_{LON} D}{2I_L f_s} \]

Where \( v_L \) equals the voltage across the inductor, \( \frac{di_L}{dt} \) equals the change in current across the inductor with respect to time, \( I_L \) equals the average current in BCM, and \( L \) equals the inductance.

**Transfer Function:**

Using property of an inductor, voltage across the inductor calculates from integration over time. The two step integrates resolve the on/off voltage difference from the source. \( T_s \) refers to the period of the switching cycle, and \( D \) refers to the duty cycle the inductor receives current.

\[
V_L = \frac{1}{T_s} \int_0^{T_s} v_L(t) dt = \frac{1}{T_s} \left\{ \int_0^{t_{ON} = DT_s} v_{LON}(t) dt + \int_{DT_s}^{T_s} v_{LOFF}(t) dt \right\} = 0
\]

\[ V_L = v_{LON} D + v_{LOFF}(1 - D) = 0 \]

**Duty Cycle Using Volts Second Balance:**

The duty cycle for ON/OFF switching cycle provides a selected output voltage for input voltage. Using volts second balance, the duty cycle (\( D \)) of the PWM determines the voltage drop across the inductor \( V_L \).

The resistor divider feedback to the IC selects output voltage \( V_{out} \). Duty cycle changes whether the value is above or below the threshold voltage property of the IC.

\[ V_L = (V_{in} - V_{out})D + (-V_{out})(1 - D) = 0 \]
\[ V_{in}D - V_{out}D - V_{out} + V_{out}D = 0 \]
\[ V_{in}D - V_{out} = 0 \rightarrow V_{out} = D \cdot V_{in} \]
\[ \frac{V_{out}}{V_{in}} = D \]
Chapter 6 includes research material into lithium ion battery charging cycles and tradeoffs between available stored energy, discharge cycles and charge time. The buck converter in conjunction with the battery regulator is designed to charge lithium ion 18650 cells. Each cell is held by strict charging and maintenance standards. Charging the cells consists of four stage cycle as seen in Figure 8: constant current and linear increase in voltage. Second, constant voltage and linear decrease in current. Third, with the batteries fully charged, current in halted. Finally, a standby mode feeds the pack small amounts of decreasing current and increasing voltage to maintain the charge. Figure 7 displays the voltage and current levels in relation to the charge capacity of the cells. Charge capacity of a cell relates to a certain voltage. Table VII displays the relation between capacity and voltage while estimating the charge time. Voltage charge level determines the longevity of lithium ion cells by the amount discharge cycles as seen in Table VIII. Charging for longevity requires a lower voltage on the cell and less available energy storage. This marks the longevity to stored energy trade-off. The next chapter includes design iterations and design decision.

BatteryUniversity.com
Lithium Ion Cells: 18650
Nominal Voltage: 3.7 V
Charge Voltage: 4.17V - 4.23V per cell
Charge for longevity: 3.8V
Charge current: 0.5C-1300mA | 1.0C – 2600 mA
2600mAh

Battery Bank:
Three in series | Two strings in parallel
Nominal Voltage: 11.1V
Charge Voltage: 12.51V – 12.69V
Charge for longevity: 11.4V
Charge current: 0.5C - 2600mA | 1.0C – 5200mA
5600mAh @ 11.1V
Figure 8: Volts/capacity vs. time when charging lithium-ion [14]

Figure 9: Charge stages of lithium ion [14]
### TABLE VII

**CELL VOLTAGE CHARGE TIME [14]**

<table>
<thead>
<tr>
<th>Charge V/cell</th>
<th>Capacity at cut-off voltage</th>
<th>Charge time</th>
<th>Capacity with full saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.80</td>
<td>60%</td>
<td>120 min</td>
<td>~65%</td>
</tr>
<tr>
<td>3.90</td>
<td>70%</td>
<td>135 min</td>
<td>~75%</td>
</tr>
<tr>
<td>4.00</td>
<td>75%</td>
<td>150 min</td>
<td>~80%</td>
</tr>
<tr>
<td>4.10</td>
<td>80%</td>
<td>165 min</td>
<td>~90%</td>
</tr>
<tr>
<td>4.20</td>
<td>85%</td>
<td>180 min</td>
<td>100%</td>
</tr>
</tbody>
</table>

### TABLE VIII

**CELL CHARGE VOLTAGE VS. DISCHARGE CYCLES [14]**

<table>
<thead>
<tr>
<th>Charge level (V/cell)</th>
<th>Discharge cycles</th>
<th>Available stored energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4.30]</td>
<td>[150–250]</td>
<td>[110–115%]</td>
</tr>
<tr>
<td>4.25</td>
<td>200–350</td>
<td>105–110%</td>
</tr>
<tr>
<td><strong>4.20</strong></td>
<td><strong>300–500</strong></td>
<td><strong>100%</strong></td>
</tr>
<tr>
<td>4.15</td>
<td>400–700</td>
<td>90–95%</td>
</tr>
<tr>
<td>4.10</td>
<td>600–1,000</td>
<td>85–90%</td>
</tr>
<tr>
<td>4.05</td>
<td>850–1,500</td>
<td>80–95%</td>
</tr>
<tr>
<td>4.00</td>
<td>1,200–2,000</td>
<td>70–75%</td>
</tr>
<tr>
<td>3.90</td>
<td>2,400–4,000</td>
<td>60–65%</td>
</tr>
<tr>
<td>3.80</td>
<td>See note</td>
<td>35–40%</td>
</tr>
<tr>
<td>3.70</td>
<td>See note</td>
<td>30% and less</td>
</tr>
</tbody>
</table>
Chapter 7 includes two design iterations of the Buck Converter, simulation results, and calculation for the network around the PWM’s IC. Design Iteration 1 considered a large input voltage and high out power with a max load current of 5A. Design Iteration 2 considered size and space as the most important factor. The portability criteria of the converter drove the decision to Design Iteration 2. While this circuit requires less board space it also handles typical portable solar panel’s electrical characteristics and battery charging controllers required power. The next chapter documents the test and analysis of the chosen design.

**Design Iteration 1:**

Design iteration 1 used the Maxim Integrated MAX17506 IC as the PWM. The design operated as a flyback converter with an external inductor. Figure 10 displays the circuit for the given values:

Maxim Integrated: MAX17506  
Vin: 4.5V – 60V  
Io = 5A  
Vout max: 54V: 2200 Hz

Figure 11 and figure 12 record the input/output comparison. Figure 11 represents an input pulse where the input steps down from 29V to 18V. From this pulse, the output response contains droop analysis and recovery time for output voltage regulation. Figure 12 also provides the output ripple voltage recorded at 20mV.
Figure 10: Design schematic for MAX17506

Figure 11: Input Voltage
Design Iteration 2:
Design Iteration 2 was developed with the Texas Instruments MC34063AP IC. Seen in figure 13, this IC includes an internal compensation reference, a comparator, an oscillator, a PWM controller with active current limiting, a driver and a high-current output switch. The internal switch reduces space and enables a more compact design. After calculation of the network around the IC, figure 14 shows the buck converter design. Extra filter capacitance added controls input/output ripple and noise. The capacitor C3 added to the circuit dampens ringing on the sense resistor that might cause voltage fluctuations.

Figure 12: Output Voltage and Current
Figure 13: MC34063 Function Diagram

Figure 14: Design 2
MC34063 Calculation:

Resistor divider R1 and R2 sets the output voltage by regulating the threshold voltage pin 5. This voltage connects to a comparator that controls the PWM and switching of the inductor. The input to this network in the output voltage feedback. Selecting a typical R1 value the following equation solves for the R2 value with a given Vout value.

\[ V_{out} = 1.25 \cdot \left(1 + \frac{R2}{R1}\right) \rightarrow R2 = \left(\frac{V_{out}}{1.25} - 1\right) \cdot R1 \]

The time on/off values for a given clock cycle calculated from the following equation where: \(V_F\) equals the voltage drop across the diode, \(V_{sat}\) equals the saturation voltage of the Darlington pair transistors, and \(V_{in(min)}\) equals the minimum allowed input voltage.

\[ \frac{t_{on}}{t_{off}} = \frac{V_{out} + V_F}{V_{in(min)} - V_{sat} - V_{out}} \]

Adding the time on/off values gives the period of oscillation or the frequency inverse.

\[ (t_{on} + t_{off}) = \frac{1}{f} \]

Using the time on value, the timing capacitor chosen uses the following equation sets the switching frequency of PWM.

\[ C_T = 4.0 \times 10^{-5} \cdot t_{on} \]

Multiplying the Maximum output current by 2 calculates the peak current of the switch.

\[ I_{pk(switch)} = 2I_{out(max)} \]

The following equation provides minimum inductance value of the inductor. This value contains a baseline for choosing the inductor’s actual value. Theory on magnetic design uses a more thorough approach to choosing the final value.

\[ L_{min} = \left(\frac{V_{in(min)} - V_{sat} - V_{out}}{I_{pk(switch)}}\right)t_{on(max)} \]

The following equation calculates output filter capacitance. This value affects the output ripple voltage of the converter.

\[ C_0 = \frac{I_{pk(switch)}(t_{on} + t_{off})}{8 \cdot V_{ripple(pp)}} \]
Results:
Table IX displays the calculation results given the values:
Vout = 12V
R1 = 1.2 kΩ
VF = 0.7V
Iout max = 1.5A
Vripple = 0.3V

Table X contains the stress sheet analysis for all components in the buck converter. After breadboard testing, the buck converter soldered to a development board completes the circuit design as seen in figure 15. Figure 16 displays the full system: buck converter connected to solar panel and battery charging station.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>toff</td>
<td>3.76 us</td>
</tr>
<tr>
<td>ton</td>
<td>26.5 us</td>
</tr>
<tr>
<td>Ct</td>
<td>1.06 nF</td>
</tr>
<tr>
<td>Rsc</td>
<td>0.4 mΩ</td>
</tr>
<tr>
<td>Lmin</td>
<td>63.7 uH</td>
</tr>
<tr>
<td>Co</td>
<td>5.68 uF</td>
</tr>
<tr>
<td>R2</td>
<td>10.3 kΩ</td>
</tr>
</tbody>
</table>

Table IX
MC34063 CALCULATION RESULTS

Table X
STRESS SHEET ANALYSIS

---

<table>
<thead>
<tr>
<th>Ref</th>
<th>Type</th>
<th>Part#</th>
<th>Value</th>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>IC</td>
<td>MC33063</td>
<td>PWM</td>
<td>40</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>L1</td>
<td>Inductor</td>
<td>744732102</td>
<td>220uH</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D1</td>
<td>Diode</td>
<td>SB240-E3/54</td>
<td>Schottky</td>
<td>40</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td>C1</td>
<td>Pol. Cap</td>
<td>100uF</td>
<td>50</td>
<td>40</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>Pol. Cap</td>
<td>100uF</td>
<td>50</td>
<td>40</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>C3</td>
<td>Pol. Cap</td>
<td>68uF</td>
<td>63</td>
<td>50.4</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>C7</td>
<td>Ceramic Cap</td>
<td>A102/1540GF5TAA</td>
<td>1mF</td>
<td>50</td>
<td>45</td>
<td>30.2</td>
</tr>
<tr>
<td>C4</td>
<td>Pol. Cap</td>
<td>10uF</td>
<td>50</td>
<td>40</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>C5</td>
<td>Pol. Cap</td>
<td>47uF</td>
<td>35</td>
<td>28</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Rsc</td>
<td>Sense Resistor</td>
<td>ws.39</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R2</td>
<td>Resistor</td>
<td>1200</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>R3</td>
<td>Resistor</td>
<td>10000</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 15: Buck Converter Assembled Circuit

Figure 16: Lithium Ion Solar Charging System
Chapter 8 includes the test results performed on the finished Buck Converter with the MC34063 chip. First, no load voltage regulation measured output voltage levels with respect to various input voltage levels. Second, timing capacitor wave measured frequency of oscillation of the functioning PWM. Third, input/output voltage and current measurements under load were used to calculate performance and efficiency. Lastly, a screen captured measured output ripple voltage. The next chapter documents testing in a fully functioning system.

No Load Voltage Regulation:

Before applying a load, voltage regulation tested input voltage responses. Input voltage set to desired output voltage (12V) seen in figure 17 shows the converter outputs 11.2V. Increasing the input voltage to 13V shows a jump to 11.8V seen in figure 18. In figure 19, input voltage increased to 14V shows a small jump to 11.844V. Figure 20 and figure 21 with input voltage 16V and 17V still increase output voltage to 11.94V and 11.99V. An input voltage of 18V reaches the 12V desired output seen in figure 22. Figure 23 display the output voltage regulating at 12.14V with an input of 24V.

Channel 1 (yellow): Input Voltage

Channel 2 (green): Output Voltage

Figure 17: No Load Vin = 12V, Vout = 11.2V
Figure 18: No Load Vin = 13V, Vout = 11.8V

Figure 19: No Load Vin = 14V, Vout = 11.8V
Figure 20: No Load Vin = 16V, Vout = 11.9V

Figure 21: No Load Vin = 17V, Vout = 12V
Figure 22: No Load Vin = 18V, Vout = 12V

Figure 23: No Load Vin = 24V, Vout = 12.1V
Timing Capacitor:
The timing capacitor $C_t$ measurement seen in figure 24 provides the switching frequency of PWM. This measurement provides useful information for stress analysis by making sure the voltage does not exceed the rating of the capacitor.

Figure 24: Timing capacitor ($C_t$) waveform
Efficiency and Voltage Regulation Load:
Efficiency measured by constant voltage with increasing load and constant load with varying voltage contains this section and raw data can found here. Overall this designs performed higher efficiencies than the MC34063 buck converter constructed in the datasheet: 25V to 5V, 500mA, 83.7% efficiency. Figure 15 provides efficiency at various input voltages by increasing the load current. In figure 25, input voltages of 30V and 32V overlap in efficiency as well as input voltages 25V and 28V. Higher input voltage operate at lower efficiency but enable the converter to reach a higher load current because the lower input current needed. Lower input voltages as 15V and 17V recived high efficiency (~93%) at 0.1A to 0.2A but cannot exceed past 0.25A. Also, lower input voltage run into a small decrease in voltage regulation seen in figure 26. The output voltage values decrease to 11.5V at 0.1A and 0.15A. The battery charging stage receives voltages down to 5V preventing any problems to arise in this application. Input voltage at 14V cannot regulate 12V at any load above 50mA. Input voltage at 32V regulates within 0.1V of 12V up to 0.46A. Figure 27 displays constant load with rising voltage and the respective voltage regulation. At 0.25A voltage regulation and efficiency from 24Vin to 26Vin shows the greatest increase.

Figure 25: Load Current vs. Efficiency at Various Input Voltages
Figure 26: Voltage Regulation under Load

Figure 27: Input Voltage vs Efficiency and Output Voltage
**Output Ripple Voltage:**

Figure 28 displays the output/input ripple voltage at no load. Figure 29 displays the output ripple voltage at 660mV where input voltage equals 28V and load equal 0.25A. The frequency equals 3.28 kHz under these conditions.

![Figure 28: Output Ripple Voltage at No Load](image1)

![Figure 29: Output Ripple Voltage at Vin = 28V, Load = .25A](image2)
Chapter 9 contains test data on the full system: Solar Panel, Buck Converter, and lithium ion battery charging. Table XI presents the electrical characteristics of the solar panel. It is important that the electrical properties of the solar panel do not damage the buck converter. The open circuit voltage, known as the highest voltage the panel produces, does not exceed the 30V derated input voltage of the IC in the buck converter. The short circuit voltage of the panel, the highest capable current of the solar panel, feeds through the sense resistor, Rsc, and gives a 232 mV drop across the resistor. This value is below the 250 mV minimum threshold voltage of the current sense pins which controls over current protection. The maximum voltage, $V_{p_{\text{max}}}$, and maximum current $I_{p_{\text{max}}}$, values represent typical operating values under load. The battery charging stage expects a range of $+5 – 12\text{VDC}$ at a maximum of $2\text{A}$. Checking back with figure 27, the maximum input voltage defined by the solar panel of $21\text{V}$ regulates just below $12\text{V}$. Figure 30 displays the solar panel’s measured open circuit voltage at $21.10\text{V}$. The buck converter connected to the solar panel regulates $11.62\text{V}$ at the output seen in figure 31. Figure 32 displays the full system charging lithium ion batteries. The solid blue lights on the battery docking station signal successful charging of the batteries. The next chapter provides references used throughout this project.

### Table XI

<table>
<thead>
<tr>
<th>Model</th>
<th>$P_{\text{max}}$</th>
<th>$I_{p_{\text{max}}}$</th>
<th>$V_{p_{\text{max}}}$</th>
<th>$I_{sc}$</th>
<th>$V_{oc}$</th>
<th>Operating Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-10W18V</td>
<td>10W</td>
<td>0.55A</td>
<td>18V</td>
<td>0.61</td>
<td>21V</td>
<td>-40 – +85°C</td>
</tr>
</tbody>
</table>

*Figure 30: Solar Panel’s Measured Open Circuit Voltage*
Figure 31: Buck Converter's Output Voltage with Solar Panel Input

Figure 32: Full System Charging Batteries
-Chapter 10-

Chapter 5 provides the literature search citations for the DC to DC Buck Converter. The following references include professionals' articles, textbooks, websites, datasheets, and patients. The next section, Appendix D, contain ABET Senior Project Analysis.

References:


[16] Texas Instruments, MC3x063 1.5-A Peak Boost/Buck/ Inverting Switching Regulators, Datasheet, Web. 06/01/17


Appendix D:

Project Title: DC to DC Buck\(^1\) Converter

Student’s Name: Kyle Roman  
Student’s Signature: 

Advisor’s Name: David Braun  
Advisor’s Initials:  
Date: 12/5/17

1. **Summary of Functional Requirements:**
   The DC to DC Buck Converter receives voltages between 14V and 40V and steps down the voltage to 12V. The regulated output provides a maximum of 1.5 amperes of current. A sense resistor with a minimum threshold voltage of 250mV provides the converter with over current protection. The input voltage to the converter also supplies power to the integrated chip that controls pulse width modulation. The converter acts as the regulator component of a solar charge controller. The system’s convenience factor includes portability and ease of connection.

2. **Primary Constraints:**
   The DC to DC Buck Converter design contains transistor level understanding of power electronics. Design at this level affects the functional capabilities, specifications, tolerance levels, and overall performance limited through parts, integrated chips, discrete components (inductors and capacitors), tolerances, and manufacturing. Monetary availability and time frames limit the quality and performance the DC to DC converter achieves.

3. **Economics**
   The DC to DC Buck Converter relies on chip manufactures, materials manufactures, use of software, and test equipment knowledge. Human capital includes research and development, testing, and device assembly. Financial capital enables the product to reach manufacturing commercially. Investors and loans with enough monetary value enables production of the device on a scale in the thousands. Manufactured or real capital included machines that manufacture integrated circuits, discrete components, testing equipment (Oscilloscopes, digital multimeters, power supplies, function generators) and design software (LT spice, SolidWorks, AutoCAD, Eagle Schematics, Vivado). Natural capital includes the material used by the device including but not limited to: copper, silicon, aluminum, plastic, stainless steel, and rubber.

   The device cost occurs during development and manufacturing stages. First, development includes exclusive costs such as testing equipment, labor, software, and extra components. During manufacturing profits are made by producing and selling enough devices. This device profits the developers and manufactures. These profits depend on the current trends or photovoltaic systems.

   The device functionality never loses its value. As technology improves this device must go through modification in design to compete with newer devices. The longevity the device can
sustain in estimated around 10 years. Maintenance may include battery changing (every 1 -2 years), and connector replacement (5-8 years).

4. **If manufactured on a commercial basis**
The growth of photovoltaic systems dictates the supply and demand of this DC to DC Buck converter. In quarter three of 2016 a new megawatt of solar energy was added to the grid every 32 minutes and a new installation was added every 84 seconds [13]. This means roughly 93,800 solar controllers needed to support those systems in that quarter alone. If this converter takes 1% of the market it has potential to sell roughly 3,700 devices in that year.

- Estimated Devices sold annually: 3,700
- Estimated manufacturing cost for each device: $10.00
- Estimated purchase price for each device: $50.00
- Estimated profit annually: $148,000.

5. **Environmental**
Developing and manufacturing the DC to DC Buck converter yields very little environmental concern. First, no harmful substances or chemicals used in the process of making the device. Manufacturing and mining the materials used in components of the product contain the environmental impact of the system.

Silicon: Silicon includes use in the buck converter’s switching controller, discrete transistors, and the solar panel. The semiconductor qualities of silicon make it essential to use in any modern day electrical circuit. To control silicon’s electrical properties, intrinsic silicon it is doped with small amounts of boron, gallium, phosphorous, or arsenic. Silicon is one of the most useful elements to mankind and is also the second most abundant element in the earth’s crust. Wafer fabrication of silicon involves the purification of raw silicon by removing impurities.

Plastic: Plastic includes use in the casing around the Lithium ion cells and some circuit components. Petroleum, natural gas, or other non-renewable resources dominate the power generation used when making plastic [17]. Environmental impact of plastic includes the destruction of fragile ecosystems from improper recycle practices and carbon pollution from petroleum use.

Lithium-ion: Lithium is most commonly found in South America in rich areas such as the Andes Mountains but can also naturally occurs in US and China. The mineral mined from rock that most often locates in briny underground ponds.

Copper: Copper, a naturally occurring element, contains many useful properties in engineering and manufacturing. Copper electrically conductive property makes it especially useful in electrically engineering. The world production of copper amounts to 12 million tons a year and exploitable reserves amount to 300 million tons, which expects to last for only another 25 years.
Less than one percent of exploits come from recycling, The Buck Converter uses copper throughout the entire system. The conductive wiring, lithium ion cells, and circuit its self all include copper. Much of the copper introduced into the environment happen naturally through wild, decaying vegetation, forest fires, and sea spray, but some is released by human activity. Copper because harmful to humans when soluble copper compounds dissolve in water supply.

6. **Manufacturability**
The process of manufacturing the device combines the products of many manufactures to one central location for assembly. The chip manufacture Texas Instruments supplies the integrated circuit mouser distributes along with discrete components and the PCB board. The casing manufacture chosen, and Mouser sends all product to a central location to complete a soldered circuit and assembled device.

7. **Sustainability**
Copper, silicon, lithium ion, plastic and aluminum make sustainable of the Buck Converter reliant on the sustainability of these materials. The device longevity depends on the weather conditions and handling conditions it endures. In the worse conditions the device operates correctly for three years and in best condition the device operates correctly of ten plus years.

8. **Ethical**
Utilitarianism motive drives the need for an energy sustainable future. Developing the DC to DC Buck Converter follows the Platinum Rule of ethical frameworks. Customers want treatment with honesty and integrity. The product performs as described and gives the customer their money’s worth. First, the device meets specifications and requirements displayed in Chapter 2. First, the device’s requirements and specifications does not leave out certain criteria that would change understand of application and limitation. Most importantly, the device does not expose the user to danger in normal operation.

Adequate research practices enable understanding of MLPE and specifically Buck converters. Patents and copyright reviewed develop an understanding to the design of other engineers.

9. **Health and Safety**
Health and safety of any person handling the DC to DC Buck converter takes an important role in developing the device. Operational current and voltage levels of the Buck Converter Reverse connection, temperature, overload, and short circuit protection all protect the user against these. The converter does not resemble a high current or high voltage electronic device. Exposure to the device’s current or voltage will not cause death.

10. **Social and Political**
The DC to DC Buck converter supports the framework of sustainable energy. This product then jeopardizes other methods of energy generation such as coal and oil. Political preference toward energy generation impacts the preference for PV system. Current tax breaks in California and other states directly impact the desire for the PV systems therefore the need for the DC to DC Buck converter. The current president Donald Trump publicly announced his disbelief in global
climate change therefore changing the possibility of tax credits changing. The president also supports energy generation from oil and coal which could affect public opinion. Public opinion could persuade people from getting solar.

11. Development
Developing the DC to DC Buck Converter required a transistor level understanding of power electronics. Literature search revealed that there many topologies for DC to DC Buck converters and each contain pro and cons. First, there exists simple buck converter topologies known as the switching converter topologies. These circuits include a capacitor, inductor, diode, and a MOSFET controlled switch [5]. For a Buck Converter implementation into a solar controller the regulation of current and voltage aligns with battery charging cycles. Programs used in development of the product include: SolidWorks, LTSpice, Microsoft Excel, PowerPoint, Word, Dip Trace, and Eagle. Device testing requires knowledge to operate oscilloscopes, power supplies, multimeter, electronic loads, and function generators.