Current-Source DC-DC Converter

A Senior Project
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In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Science

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Abstract

In this project, a hardware implementation of a current-source DC-DC converter for powering sensors used in an underwater communications system is presented. The proposed converter is designed to step down an input current of 0.9 A to 0.625 A, while maintaining an output voltage of 24 V and output power of 15 W. An overview of the system design is explained as well as the component selection process. The design of the converter was simulated and evaluated using LTspice before being physically constructed on a printed circuit board. Performance evaluation of the proposed converter was carried out in multiple lab tests while varying the input current, duty cycle, and load size. Results of the lab tests demonstrate the proof of concept of the design and the expected trends that are consistent with the previously derived transfer function of the converter.
Chapter 1: Introduction

Communication systems have become an essential part of how information is exchanged in the current world. From the invention of the telegraph, technology has rapidly evolved to the point where information is able to be relayed from one end of the planet to another within seconds. A communication system is defined as a method through which information from a source (the transmitter) is transferred to a destination (the receiver) via a channel (the propagation medium) [1]. This encompasses many of the devices that are used today to send messages from one location to another. One of the devices that would fall into this category is fiber optics.

An optical fiber is used to send information in a safe and effective manner. The fiber is slightly thicker than a human hair and contains a glass core that can transmit light signals with minimal loss in strength. Fiber optic cables are created when multiple optical fibers are bundled together. These interconnections are great for sending data because of their low transmission loss, small space requirements and light weight. The bundled transmission also has an integration advantage for bandwidth hungry applications [2]. Optical fibers can be used as sensors, devices for power transmission, and most commonly as part of fiber optic communication systems since they are efficient transmitters. Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of infrared light through an optical fiber. The light acts as a form of carrier wave that is modulated to carry information. Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference is required. This type of communication can transmit voice, video, and telemetry through local area networks or across long distances in any type of environment. This makes these types of fibers suitable for underwater applications as shown in Figure 1-1.
However, due to the interior cabling being very small, any cut cables may result in difficult to detect and resolve potential failures.

Figure 1-1. Standard Submarine Cabling System [3].

Cable sizing varies based on water depth by requiring heavier protection at greater depths as shown in Figure 1-2. Note, this may affect current and voltage levels used within the fiber optics system to transmit data. The cables themselves are made up of multiple pairs of fibers which are coated in layers of metal and composites for protection. High levels of current and voltage travel through cables, which is produced by power feed equipment (PFE). The requirements of PFE include high reliability to avoid interruption of active communication lines, stable current feeding, overcurrent and overvoltage protection, high efficiency, and maintenance safety protocols [4].
Figure 1-2. The Sizing of Optical Undersea Fiber Optic Cables Based upon depth of the ocean [4].

One way to deliver power to these types of systems is through power electronics. Due to the continuous advancements in power electronics technology, DC-DC converters are widely used in many power apparatuses such as computers, televisions, cell phone chargers, and other electronic consumer devices. They are also used in medical, military, and telecommunications equipment; kitchen appliances; industrial machinery; and commercial products. Voltage comes in the form of alternating current (AC) and direct current (DC) both of which provide many benefits in the realm of electric circuits and energy conversion. Apart from voltage types, we can also convert from one voltage type to another. The different forms of conversion when it comes to converters include AC-DC, AC-AC, DC-AC and DC-DC [5]. Note that for this project we will be working with DC voltage only. Therefore, we will be implementing a DC-DC converter.
Chapter 2. Background

Power electronics allows the user to regulate the flow of voltage and current in a system by converting it into a form that can meet the load or user requirements [5]. There are different types of categories of power electronics converters which consist of AC-DC, AC-AC, DC-AC and DC-DC converters. Many electrical energy applications today are performed by power electronics. Due to this, power electronics has become the main source for different future applications. There are many factors that are important while using power electronics including efficiency, reliability, cost and component sizing that complement design. In real world applications, reliability is critically important because it determines the overall performance of the product.

DC-DC converters efficiently convert and regulate voltage from one DC value to another DC value. This is useful in appliances where a constant voltage is required. There are many different DC-DC converter topologies based on the position of the switch, diode, and inductor. Among these DC-DC converter topologies are buck, boost, and buck-boost. Each topology contains its respective uses along with its pros and cons. For example, the buck converter is known as a “step down” converter because it steps down the voltage. The boost converter “steps up” the voltage and a buck-boost implements both “step up” or “step down”. Typically, some of the main pros and cons of each topology lie in the efficiency, ease of use, and duty cycle. The benefits and application of each topology are crucial in determining which type of DC-DC converter would be most convenient for a given scenario. The benefits and application of each topology are crucial in determining which type of DC-DC converter would be most convenient for a given scenario. Figure 2-1 & Figure 2-2 show the basic configuration used in this type of converter.
DC-DC converters are used when a primary DC source needs to deliver power to several parts that require a DC voltage that is different from the source. The output voltage is controlled by a DC-DC converter. Based on the choice of circuit or topology, the DC-DC converter can produce voltages and currents that are higher, lower, or equal to those of the input.

A solid-state transformer usually contains a transformer inside the AC-to-AC converter or DC-to-DC converter, which provides electrical isolation and carries the full power. This transformer is smaller due to smaller DC-DC inverting stages between transformer coils. This means that smaller transformer coils are required to step up or step down voltages. A solid-state transformer can actively regulate voltage and current. Some can convert single-phase power to
three-phase power and vice versa. Variations can input or output DC power to reduce the number of conversions for greater end-to-end efficiency.

One example of a Current-Source DC-DC converter developed to step down voltage was demonstrated in [7]. In this paper, a current-source converter for use in photovoltaic systems as shown in Figure 2-3 was proposed and simulated in EMTDC/PSCAD software. Photovoltaic systems require power electronic converters as they act as the interface between input sources and the load to generate desirable outputs [8][9]. In this topology, zero current switching of primary-side devices and zero voltage switching of secondary-side devices are obtained. This minimizes switching losses as well as voltage and current stresses on power electronic devices.

![Dual-output step-down soft switching current-fed full-bridge DC-DC converter](image.png)

Figure 2.3 Dual-output step-down soft switching current-fed full-bridge DC-DC converter [7].

In this converter design, diodes D1- D8 are the internal diodes of switches S1-S8 and capacitors C1-C8 represent the parasitic capacitor of switches S1- S8. The duty cycle of switches S1-S4 must be greater than 50% while the duty cycle of switches D5-D8 must be less than 50% [7]. The input inductor, L decreases the input current ripple. The leakage inductance $L_K$, and
parallel parasitic capacitors with the switches provide soft switching operation. In this design, $C_{01}$ and $C_{02}$ are output filter capacitors and dual-outputs for the design are provided using a three-winding transformer on the secondary side. In this topology, after turning on the pair of switches S1 and S4 on the primary-side as well as S6 and S7 on the secondary-side, the other pairs (S2 and S3) and (S5 and S8) are turned off.

The system components are sensitive to a wide variety of stressors, which can lead to problems affecting the safety of the system. These problems can have serious impacts on the system's reliability, which can result in potentially dangerous situations. Therefore, careful selection of component sizing, ratings, and reliability will be key for optimal operation of the system. Besides the current source approach, there are alternatives in achieving high input to output gain while maintaining efficiency. This includes for examples resonant converters as presented in many papers such as [10]-[13].

This project will emphasize the usage of DC-DC converters with regards to powering subsystems used in monitoring submarine fiber optic cables. More specifically, this project aims to study, design, and build a current-source DC-DC converter modeled to power underwater sensors that operate with low level DC electricity found within underwater repeater capsules.
Chapter 3: Design Requirements

In terms of electrical specifications, the converter will receive a maximum input current of 1A and a maximum DC input voltage of 1500V. Both will have a tolerance of ±5%. The device will then convert the input to a DC voltage of 24V with a voltage ripple less than 2%. The output current will be 0.625A which will generate the output power of 15W needed to operate the sensors within the submarine repeater. Figure 3-1 depicts the high-level design of the proposed DC/DC converter.

![System Level 0 Block Diagram](image)

Figure 3-1. System Level 0 Block Diagram

In order to maintain the output voltage at a constant value of 24V, a feedback controller must be implemented. If there is a sudden change in the input current, the feedback controller will account for change and compensate accordingly. To keep the heat dissipation of the converter at a minimum, the power efficiency of the converter should be at least 80% at full load. Figure 3-2 depicts the design with the addition of the feedback controller.
In terms of physical specifications, the converter will be housed within a pressurized vessel in the underwater system. The vessel will be formed from a copper material and will take on a cylindrical shape. Its length will be 80cm and will have a diameter of 22cm. The proposed DC/DC converter must be implemented on a circuit board that is able to fit within these physical dimensions. Figure 3-3 portrays the physical specifications of the submarine housing.
Table 3-1 gives a summary of the discussed physical and electrical specifications order to meet the requirements of the user.

Table 3-1. Summary of System Requirements for Current-Source DC/DC Converter

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Converter Electrical Specification</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum Input Current</td>
<td>1A</td>
</tr>
<tr>
<td>Average Output Voltage</td>
<td>24V DC</td>
</tr>
<tr>
<td>Maximum Output Current</td>
<td>0.625A</td>
</tr>
<tr>
<td>Maximum Output Power</td>
<td>15W</td>
</tr>
<tr>
<td>Output Voltage Ripple</td>
<td>&lt; 2%</td>
</tr>
<tr>
<td>Overall Efficiency</td>
<td>≥ 80%</td>
</tr>
<tr>
<td>Load Regulation</td>
<td>≤ 5%</td>
</tr>
<tr>
<td>Line Regulation</td>
<td>≤ 5%</td>
</tr>
<tr>
<td><strong>Converter Physical Specification</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>≤ 80cm</td>
</tr>
<tr>
<td>Width</td>
<td>≤ 20cm</td>
</tr>
</tbody>
</table>
Chapter 4: System Design

The DC-DC converter configuration is designed to convert an input current of 0.9 A to a constant voltage of 24 V with an output current of 0.625 A to yield an output power of 15 W. The proposed current source DC-DC converter consists of a primary and secondary side utilizing a transformer. The primary side consists of a full bridge inverter while the secondary side utilizes a rectifier. An open loop system of this design will be implemented in hardware. The input will be adjusted manually in order to achieve the desired output of 24V. This system is illustrated in Figure 4-1.

![Figure 4-1. System Block Diagram.](image)

4.1 Current Source DC-DC Converter Design Overview

The simplified model of the power stage of the proposed current source DC-DC converter is depicted in Figure 4-2.

![Figure 4-2. Simplified Current Source DC-DC converter.](image)
The transfer function of the circuit is given in equation 4-1.

\[
\bar{V}_{out} = \bar{V}_{in} \frac{N_s}{N_p} \frac{1}{2(1 - D)} 
\]  

(4-1)

4.2 Transformer Selection

In order to achieve the desired output voltage, the turns ratio for the transformer is chosen to be 2:1. The converter is designed to operate at a frequency of 250kHz. In order to meet these specifications, the Wurth Elektronik 750319069 transformer was chosen. This transformer can support multiple turns ratio and the configuration of the pins are shown in Figure 4-3.

![Transformer Configuration](image)

Figure 4-3. Transformer Configuration

The terminals 1+2, 5+6, 7+8, and 11+12 are connected while N1 and N3 are used to create a turns ratio of 2:1. N2 is left open as it is not needed to create this ratio as shown in Table 4-1.
4.3 Switch Selection

The equation for the switch voltage rating is shown in equation 4-2.

\[
V_{SW1} = V_{SW2} = V_{SW3} = V_{SW4} = \frac{N_p}{N_s} V_{out}
\]  

(4-2)

Given the turns ratio of 2:1 and a desired output voltage of 24V, the voltage rating for each switch will be 48V. The equation for the average switch current is shown in equation 4-3.

\[
\bar{I}_{SW} = \bar{I}_{SW1} = \bar{I}_{SW2} = \bar{I}_{SW3} = \bar{I}_{SW4} = \bar{I} \cdot \frac{1}{2}
\]  

(4-3)

With an input current of 0.9A, the average current through each switch is calculated to be 0.45A. In order to fit these specifications, the n-channel MOSFET SSM3K341TU is selected as it is rated for 60V and 6A.
4.3 Diode Selection

Given that the diodes are in parallel with the load at the output, the voltage across the diodes will be equivalent to the output voltage as summarized in equation 4-4. Due to output voltage being below 100V and the converter operating at a switching frequency of 250kHz, the ideal diode choice will be between a Schottky or SBR type.

\[ V_{D1} = V_{D2} = V_{D3} = V_{D4} = V_{\text{out}} \quad (4-4) \]

The equation for the current across the diodes is given in equation 4-5.

\[ I_D = I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{\text{in}} \frac{N_p}{N_s} (1 - D) \quad (4-5) \]

After using the equations to calculate the voltage and current across the diodes, it is found that the voltage must be rated for at least 24V and the current must be rated for at least 0.3132A. For this reason, the STMicroelectronics STPS5L60S Schottky diode was chosen that is rated for 50V and 6A.

4.4 Output Capacitor Selection

The equation to calculate the capacitance on the output capacitor is given below in equation 4-6.

\[ C_1 = \left( I_{\text{in}} \frac{N_p}{N_s} - I_{\text{out}} \right) (1 - D) T \frac{1}{\Delta V_o} = \left( I_{\text{in}} \frac{N_p}{N_s} - I_{\text{out}} \right) \frac{(1 - D)}{\Delta V_o f} \quad (4-6) \]

With the chosen frequency for this design of 250kHz and the assumed output voltage ripple of 0.1V, an output capacitance of 8 µF is calculated. The capacitance value will be rounded up to the standard value of 10 µF to be utilized within the design.
4.5 Simulation Results

For simulating the proposed current source DC-DC converter, the circuit schematic in Figure 4-4 was created in LTspice.

The LTC7062 was selected for the gate drivers with each taking an input of two square waves 180° out of phase with a duty cycle of 0.6 and frequency of 250kHz as shown in Figure 4-5.

![Figure 4-4. LTspice schematic of proposed converter](image)

![Figure 4-5. Input Waveforms for Gate Drivers](image)
The circuit was simulated for 1ms and the desired output voltage of 24V was achieved after reaching steady state at approximately 0.7ms.

Figure 4-6. Output voltage showing 24V

Once the simulation proves that the 24V output voltage has been achieved, the hardware prototype design follows. Based on the previous equations and component selections, the Bill of Materials were then generated as shown in Table 4-2.
Table 4-1. Bill of Materials

<table>
<thead>
<tr>
<th>Count</th>
<th>Reference Designator</th>
<th>Component Value</th>
<th>Description</th>
<th>Size (L x W)</th>
<th>Part Number</th>
<th>Manufacturer</th>
<th>Per Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>U1, U2</td>
<td>LTC7062</td>
<td>Gate Driver</td>
<td>2.85mm x 1.651mm</td>
<td>LTC7062EMSE###TRPBF</td>
<td>Analog Devices</td>
<td>$3.03</td>
</tr>
<tr>
<td>1</td>
<td>D7, D8</td>
<td>Vz: 27V, Pd: 40W</td>
<td>Zener diode</td>
<td>3.1mm x 1.43mm</td>
<td>MMBZ27VDA-HF10-03</td>
<td>Vishay</td>
<td>$0.43</td>
</tr>
<tr>
<td>4</td>
<td>M1, M2, M3, M4</td>
<td>SSM3K341T U</td>
<td>Mosfet</td>
<td>2mm x 1.7mm</td>
<td>SSM3K341TULF</td>
<td>Toshiba</td>
<td>$0.46</td>
</tr>
<tr>
<td>2</td>
<td>C2</td>
<td>10uF, ceramic</td>
<td>Capacitor</td>
<td>3.2mm x 2.5mm</td>
<td>587-1818-1-ND</td>
<td>Taiyo Yuden</td>
<td>$0.00</td>
</tr>
<tr>
<td>2</td>
<td>C4, C6</td>
<td>2.2uF</td>
<td>Capacitor</td>
<td>3.2mm x 2.5mm</td>
<td>581-1201012254T2A</td>
<td>Kyocera Avx</td>
<td>$0.00</td>
</tr>
<tr>
<td>2</td>
<td>C3, C5</td>
<td>4.7uF</td>
<td>Capacitor</td>
<td>3.2mm x 1.6mm</td>
<td>490-1809-1-ND</td>
<td>Murata Electronics</td>
<td>$0.00</td>
</tr>
<tr>
<td>3</td>
<td>R1</td>
<td>1k Ω</td>
<td>Resistor</td>
<td>3.2 x 1.6mm</td>
<td>PTN1206Y1001BST1</td>
<td>Vishay</td>
<td>$0.96</td>
</tr>
<tr>
<td>6</td>
<td>D1, D2, D3, D4, D5, D6</td>
<td>SCHOTTKY 60V 5A</td>
<td>Diode</td>
<td>5.84mm x 2.07mm</td>
<td>STPS5L60S</td>
<td>STMicroelectronics</td>
<td>$0.00</td>
</tr>
<tr>
<td>1</td>
<td>C1</td>
<td>10uF, electrolytic</td>
<td>Capacitor</td>
<td>5.3mm x 5.3mm</td>
<td>PCE3067CT-ND</td>
<td>Digi-Key</td>
<td>$0.00</td>
</tr>
<tr>
<td>1</td>
<td>L1, L2</td>
<td>2:1 turns ratio</td>
<td>Transformer</td>
<td>21.8mm x 11.43mm</td>
<td>750319069</td>
<td>Wurth Elektronik</td>
<td>$10.91</td>
</tr>
</tbody>
</table>
4.5 PCB Design

To construct a hardware prototype, the first step is to create a schematic of the actual circuit that will later be built on a printed circuit board (PCB). Figure 4-7 depicts the schematic for the current source converter. The actual board layout was then designed and generated as shown in Figures 4-8 and 4-9. When placing the components on the board layout, the power stage components should be separated from the control or signal components. Additionally, to keep signal integrity of the control circuitry, the ground signal plane is separated from the power ground to keep the switching noise out.

Figure 4-7. PCB Schematic
Figure 4-8. PCB layout hiding ground plane
Figure 4-9. PCB layout showing ground plane
Chapter 5: Hardware Test and Results

This chapter discusses the hardware testing of the proposed converter, demonstrating both the functionality and operation of the design. Before testing the board, the components were soldered onto the PCB and tested individually to ensure they functioned as intended. The final product is shown in Figure 5-1.

Figure 5-1. PCB with soldered components.
Figure 5-2. Block diagram of lab test setup.

**Equipment:**

Below is a list of equipment used for the lab test setup.

- 1 PCB
- 1 Analog Discovery 2
- 1 USB cable
- 1 Breadboard
- 1 box of male-female & male-male wires
- 1 Power Resistor Decade Box
- 6 banana- banana

**Procedure:**

To perform the hardware testing, the following steps were conducted.

1. Connect the Analog Discovery 2 and open Waveform and select wave generator 1 &2, suppliers and scope 1.
2. The set up in the Analog Discovery for waveform 1 as you can observe in Figure 5-3.
- Type: Square Wave
- Frequency: 250 kHz
- Period: 4 us
- Amplitude: 2.5V
- Offset: 2.5V
- Symmetry: 60%
- Phase: 0°

Note that in order to adjust the duty cycle the symmetry was changed to any percentage needed.

![Figure 5-3. Parameters Utilized in Analog Discovery Waveform 1.](image)

3. Do the same thing for waveform 2, but in this case change the phase to 180°.

![Figure 5-4. Parameters Utilized in Analog Discovery 2 Waveform 2.](image)
4. Set the supplier to +5V and -5V and connect it to VCC from the PCB.

5. Once per set-up, plug the Power Resistor Decade Box to the outputs on the right side of the PCB.

6. Connect the power supply to the input

7. Connect the multimeter to the output

8. Connect Scope Channel 1 to VIN1(Orange) and waveform 1(+)

9. Connect Scope Channel 2 to VIN2(Blue) and waveform 1(-)

10. Connect VCC to the V+ power supply (+5Vdc -Red wire)

11. Signal ground connects to the same Ground as Channel 1(-) and Channel 2(-)

12. From the AD2, select synchronized channel. Adjustments for 1 waveform also changes for waveform 2.

13. To avoid any discrepancies, use a breadboard and connect male-female wires from the PCB to the breadboard.
Figure 5-5. PCB Labeled with inputs & outputs.

Figure 5-6. Complete Setup of DC-DC- converter.
Figure 5-7. PCB with inputs & outputs connected

Figure 5-8. Power Resistor Box for $R_O$ & Load
Figure 5-9. DC Power Supplier with maximum current limit at 0.9 and 6V.

Figure 5-10. Analog Discovery 2 Breadboard Connections and Set-up.

Test Cases:

Case I:

Table 5-1 shows the relationship between the output voltage and varying the load with respect to a constant duty cycle (70%) and constant currents of 0.9A, 0.8A and 0.7A respectively. A 70% duty cycle was chosen for consistency of results. As expected via ohm’s law, for a constant current we have an increasing relationship for the output voltage as we
increase the output load. For the 3 sets of data, output voltage variations are present, but the overall trend is consistent with expected output results.

Table 5-1. Vary Load under Constant current & duty Cycle.

<table>
<thead>
<tr>
<th>Ro (Ohms)</th>
<th>Duty Cycle 70% &amp; 0.9A</th>
<th>Duty Cycle 70% &amp; 0.8A</th>
<th>Duty Cycle 70% &amp; 0.7A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>280</td>
<td>417</td>
<td>418</td>
</tr>
<tr>
<td>2000</td>
<td>369</td>
<td>424</td>
<td>425</td>
</tr>
<tr>
<td>3000</td>
<td>430</td>
<td>431</td>
<td>432</td>
</tr>
<tr>
<td>4000</td>
<td>477</td>
<td>438</td>
<td>437</td>
</tr>
<tr>
<td>5000</td>
<td>513</td>
<td>443</td>
<td>442</td>
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<tr>
<td>6000</td>
<td>545</td>
<td>448</td>
<td>448</td>
</tr>
<tr>
<td>7000</td>
<td>573</td>
<td>453</td>
<td>453</td>
</tr>
<tr>
<td>8000</td>
<td>580</td>
<td>457</td>
<td>457</td>
</tr>
<tr>
<td>9000</td>
<td>586</td>
<td>460</td>
<td>461</td>
</tr>
</tbody>
</table>

Figure 5-11. Output Voltage vs. Load With Duty Cycle at 70%
Case II:

Table 5-2 shows the relationship between the output voltage and varying the current with respect to a constant duty cycle (70%) and constant loads of 2000Ω, 3000Ω and 4000Ω respectively. 70% duty cycle was chosen for consistency of results. As expected via ohm’s law, we now have for a constant load an increasing relationship for the output voltage as we increase the input current. One observation to be made is the overall output voltages are much higher for the data at 3000Ω and 4000Ω rather than the 2000Ω. However, for the 3 sets of data, output voltage variations are once again present, but the overall trend is consistent with expected output results.

Table 5-2. Vary Current under constant duty Cycle, constant load.

<table>
<thead>
<tr>
<th>Duty Cycle 70% with Load 2000Ω</th>
<th>Duty Cycle 70% with Load 3000Ω</th>
<th>Duty Cycle 70% with Load 4000Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>In (A)</td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
</tr>
<tr>
<td>0.5</td>
<td>133</td>
<td>189</td>
</tr>
<tr>
<td>0.55</td>
<td>143</td>
<td>203</td>
</tr>
<tr>
<td>0.6</td>
<td>158</td>
<td>224</td>
</tr>
<tr>
<td>0.65</td>
<td>180</td>
<td>256</td>
</tr>
<tr>
<td>0.7</td>
<td>208</td>
<td>301</td>
</tr>
<tr>
<td>0.75</td>
<td>241</td>
<td>373</td>
</tr>
<tr>
<td>0.8</td>
<td>280</td>
<td>466</td>
</tr>
<tr>
<td>0.85</td>
<td>324</td>
<td>562</td>
</tr>
<tr>
<td>0.9</td>
<td>402</td>
<td>603</td>
</tr>
</tbody>
</table>
Figure 5-12. Output Voltage vs. Input Current With Duty Cycle at 70%

Case III:

Tables 5-3 and 5-4 show the relationship between the output voltage and increasing the duty cycle for 2000Ω and 3000Ω respectively. Based on the equation for duty cycle and the relationships between duty cycle, output voltage and input voltage, there should be an increasing trend for the output as duty cycle increases. This is because increasing the duty cycle increases our input voltage yielding higher output voltages which is consistent with both obtained data sets. Furthermore, due to ohm's law, voltage outputs for 3000Ω should typically be higher than the 2000Ω load because of the increased resistance which is consistent across the two tables.
Table 5-3. Vary Duty Cycle under constant current & Load (3000Ω).

<table>
<thead>
<tr>
<th>Duty cycle (%)</th>
<th>Vo (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>301</td>
</tr>
<tr>
<td>65%</td>
<td>365</td>
</tr>
<tr>
<td>70%</td>
<td>437</td>
</tr>
<tr>
<td>75%</td>
<td>445</td>
</tr>
<tr>
<td>80%</td>
<td>456</td>
</tr>
</tbody>
</table>

Table 5-4. Vary Duty Cycle under constant current & Load (2000Ω).

<table>
<thead>
<tr>
<th>Duty cycle (%)</th>
<th>Vo (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50%</td>
<td>280</td>
</tr>
<tr>
<td>55%</td>
<td>391</td>
</tr>
<tr>
<td>60%</td>
<td>300</td>
</tr>
<tr>
<td>65%</td>
<td>320</td>
</tr>
<tr>
<td>70%</td>
<td>360</td>
</tr>
<tr>
<td>75%</td>
<td>422</td>
</tr>
</tbody>
</table>

Case IV:

Table 5-5 shows the variation of the output voltage as we increase the load for duty cycles of 40% to 70%. One observation based on the obtained results is the apparent increasing output voltage for a 1000-ohm load as we vary the duty cycle from 40% to 60%. For the 10000 load however, the output voltage swings appear to be non-linear as we vary the duty cycle from 40% to 60%.
Table 5-5. High and Low Vo for Constant current .9A, changing duty cycle

<table>
<thead>
<tr>
<th>Duty cycle (%)</th>
<th>Ro LOW (Ohms)</th>
<th>Vo (LOW Ro) mV</th>
<th>Ro HIGH (Ohms)</th>
<th>Vo (HIGH Ro) mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>1000</td>
<td>172</td>
<td>10000</td>
<td>403</td>
</tr>
<tr>
<td>50%</td>
<td>1000</td>
<td>203</td>
<td>10000</td>
<td>393</td>
</tr>
<tr>
<td>60%</td>
<td>1000</td>
<td>263</td>
<td>10000</td>
<td>365</td>
</tr>
<tr>
<td>70%</td>
<td>1000</td>
<td>362</td>
<td>10000</td>
<td>600</td>
</tr>
</tbody>
</table>

Case V:

Table 5-6 shows the relationship between the output voltage and varying the load with respect to a constant duty cycle (60%) and constant currents of 0.9A, 0.8A and 0.7A respectively. 60% duty cycle was chosen for consistency of results. Results are once again as expected with the data set for the 70% duty cycle, but voltage variations are more present. As expected via ohm’s law, for a constant current we have an increasing relationship for the output voltage as we increase the output load. For the 3 sets of data, output voltage variations are present, but the overall trend is once again consistent with expected output results as below in Figure 5-13.

Table 5-6. Vary Load with constant duty cycle, changing current.

<table>
<thead>
<tr>
<th>Ro (Ohms)</th>
<th>Duty cycle 60 % current 0.9A</th>
<th>Duty cycle 60% Current 0.8A</th>
<th>Duty cycle 60% Current 0.7A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
</tr>
<tr>
<td>1000</td>
<td>261</td>
<td>307</td>
<td>260</td>
</tr>
<tr>
<td>2000</td>
<td>310</td>
<td>310</td>
<td>264</td>
</tr>
<tr>
<td>3000</td>
<td>341</td>
<td>313</td>
<td>266</td>
</tr>
<tr>
<td>4000</td>
<td>361</td>
<td>317</td>
<td>269</td>
</tr>
<tr>
<td>5000</td>
<td>374</td>
<td>320</td>
<td>271</td>
</tr>
<tr>
<td>6000</td>
<td>384</td>
<td>322</td>
<td>274</td>
</tr>
<tr>
<td>7000</td>
<td>393</td>
<td>325</td>
<td>276</td>
</tr>
<tr>
<td>8000</td>
<td>402</td>
<td>327</td>
<td>278</td>
</tr>
</tbody>
</table>
Figure 5-13. Output Voltage vs Load with Duty Cycle at 60%

Case VI:

Table 5-7 shows the relationship between the output voltage and varying the current with respect to a constant duty cycle (60%) and constant loads of 2000Ω, 3000Ω and 4000Ω respectively. 60% duty cycle was chosen for consistency of results. Results are to be expected as with the 70% duty cycle, but more variations are shown in this new set of results. As expected, ohm’s law holds for the output voltage as input current increases and the overall trend is consistent with expectations as seen in Figure 5-14.
Table 5-7. Vary current under constant duty cycle, changing load

<table>
<thead>
<tr>
<th>Duty Cycle 60% load 2000Ω</th>
<th>Load 3000Ω</th>
<th>4000Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iin (A)</td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
</tr>
<tr>
<td>0.5</td>
<td>124</td>
<td>180</td>
</tr>
<tr>
<td>0.55</td>
<td>137</td>
<td>196</td>
</tr>
<tr>
<td>0.6</td>
<td>155</td>
<td>215</td>
</tr>
<tr>
<td>0.65</td>
<td>177</td>
<td>239</td>
</tr>
<tr>
<td>0.7</td>
<td>196</td>
<td>265</td>
</tr>
<tr>
<td>0.75</td>
<td>215</td>
<td>290</td>
</tr>
<tr>
<td>0.8</td>
<td>238</td>
<td>313</td>
</tr>
<tr>
<td>0.85</td>
<td>280</td>
<td>341</td>
</tr>
<tr>
<td>0.9</td>
<td>317</td>
<td>394</td>
</tr>
</tbody>
</table>

Output Voltage (mV) vs Input Current (A)
Constant Duty Cycle (60%), Constant Load

Figure 5-14. Output Voltage vs. Input Current with Duty Cycle at 60%
Case VII:

Table 5-8 shows the relationship between the output voltage and varying the load with respect to a constant duty cycle (65%) and 3 different cases for constant current (0.9A, 0.8A and 0.7A respectively). 65% duty cycle was chosen for consistency of results. Even more variations are found for this new set of data at 65% duty cycle and results are as expected. Comparing results with 60% and 70% duty cycles, variations are found to be more stable at 65%.

Table 5-8. Vary Load with constant duty cycle, changing current

<table>
<thead>
<tr>
<th>Ro (Ohms)</th>
<th>Duty Cycle 65% &amp; 0.9A</th>
<th>Duty Cycle 65% &amp; 0.8A</th>
<th>Duty Cycle 65% &amp; 0.7A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
<td>Vo (mV)</td>
</tr>
<tr>
<td>1000</td>
<td>290</td>
<td>280</td>
<td>225</td>
</tr>
<tr>
<td>2000</td>
<td>352</td>
<td>284</td>
<td>228</td>
</tr>
<tr>
<td>3000</td>
<td>396</td>
<td>286</td>
<td>230</td>
</tr>
<tr>
<td>4000</td>
<td>428</td>
<td>289</td>
<td>232</td>
</tr>
<tr>
<td>5000</td>
<td>453</td>
<td>291</td>
<td>234</td>
</tr>
<tr>
<td>6000</td>
<td>472</td>
<td>293</td>
<td>235</td>
</tr>
<tr>
<td>7000</td>
<td>493</td>
<td>295</td>
<td>237</td>
</tr>
<tr>
<td>8000</td>
<td>506</td>
<td>297</td>
<td>238</td>
</tr>
<tr>
<td>9000</td>
<td>518</td>
<td>299</td>
<td>240</td>
</tr>
</tbody>
</table>
Figure 5-15. Output Voltage vs. Load with Duty Cycle at 65%

Case VIII:

Table 5-9 shows the relationship between the output voltage and varying the current with respect to a constant duty cycle (65%) and 3 different cases for constant load (2000Ω, 3000Ω and 4000Ω respectively). 65% duty cycle was chosen for consistency of results. Consistent with previous expected results for 60% and 70% duty cycles, there are yet even more discrepancies between output voltage for the 65% duty cycle. Based on observation, the output trend appears most consistent at 70%, meanwhile the most variation occurs at 60%.
Table 5-9. Vary current under constant duty cycle, changing load.

<table>
<thead>
<tr>
<th>Duty Cycle 65% with Load 4000Ω</th>
<th>Duty Cycle 65% with Load 3000Ω</th>
<th>Duty Cycle 65% with Load 2000Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I_{in} (A)</strong></td>
<td><strong>V_{o} (mV)</strong></td>
<td><strong>V_{o} (mV)</strong></td>
</tr>
<tr>
<td>0.5</td>
<td>179</td>
<td>133</td>
</tr>
<tr>
<td>0.55</td>
<td>193</td>
<td>143</td>
</tr>
<tr>
<td>0.6</td>
<td>203</td>
<td>158</td>
</tr>
<tr>
<td>0.65</td>
<td>215</td>
<td>180</td>
</tr>
<tr>
<td>0.7</td>
<td>229</td>
<td>208</td>
</tr>
<tr>
<td>0.75</td>
<td>249</td>
<td>241</td>
</tr>
<tr>
<td>0.8</td>
<td>283</td>
<td>280</td>
</tr>
<tr>
<td>0.85</td>
<td>345</td>
<td>324</td>
</tr>
<tr>
<td>0.9</td>
<td>453</td>
<td>402</td>
</tr>
</tbody>
</table>

Figure 5-16. Output Voltage vs. Input Current with Duty Cycle at 65%
Duty Cycle Variation:

Figures 5-17 through 5-20 show how the duty cycle was varied on the Analog Discovery 2. Two 250KHz square waves with an amplitude of 5V were created to control the gate drivers. Channel 1 and channel 2 were being synchronized with an offset of 180 degrees. The duty cycle was increased to as much as 80% to observe its effect on the output voltage.

Figure 5-17. Duty Cycle Waveforms at 60%.
Figure 5-18. Duty Cycle Waveforms at 65%.

Figure 5-19. Duty Cycle Waveform at 70%.
Figure 5-20. Duty cycle Waveform at 80%.
Chapter 6: Conclusion

The objective of this project was to implement the current-source DC-DC converter design in hardware to provide a proof of concept to be utilized in undersea fiber optic cable sensors. The converter was designed to step down an input current of 0.9A to 0.625A, while maintaining an output voltage of 24V and output power of 15W.

Although the LTspice simulation showed an output voltage of 24V using the design, that voltage was unable to be reached in the hardware implementation. However, the concept of the design and the expected trends with regards to the output voltage were verified in the lab. The major reasons why the desired output voltage was not reached was due to the absence of the control circuit that would regulate the output voltage. Additionally, the transformer selected may not have enough inductance to provide the necessary voltage. Multiple tests were run while varying the duty cycle, input current, and load size. As the duty cycle increased, the output voltage increased. As the load increased in size, the output voltage also increased. When more current was fed at the input, a higher voltage could be seen across the output. These findings were consistent with the transfer function that was previously derived for the converter.

One area of improvement for this design would be developing a better PCB layout. Although the PCB design was sufficient enough to connect the components and test the board, shorter traces could be made to reduce losses and component placement could be improved. Creating two square waveforms that were perfectly 180° out of phase in order to control the gate drivers was poised to be a challenge with the equipment that was provided. Even though the Analog Discovery 2 generated waveforms that were close to the desired waveforms, better equipment could be used in future implementations to ensure more reliable results. Furthermore,
more troubleshooting could be done to find out why the voltage seen at the output was not as high as expected. Lastly, the transformer may have to be designed instead of purchasing it. This ensures that the correct inductances of the transformer are provided, and enough energy is delivered to the load.
References


APPENDIX — ANALYSIS OF SENIOR PROJECT DESIGN

Project Title: Current-Source DC-DC Converter

Student’s Name: Adrian Aranjo, Carlos Aguilar, Rocio Sanchez

Advisor’s Name: Taufik Advisor’s Initials: Date:

Summary of Functional Requirements

This project is a hardware implementation of a current-source DC-DC converter for powering sensors used in underwater communications. The proposed converter is designed to step down an input current of 0.9 A to 0.625 A, while maintaining an output voltage of 24 V and output power of 15 W.

Primary Constraints

Finding the appropriate equipment to control the gate drivers made the project difficult. Two square waveforms that were perfectly 180° out of phase needed to be generated. However, the Analog Discovery 2 created waveforms that sufficiently filled this requirement.

Economic

The cost of the DC-DC converter is mainly dependent on the hardware and electrical components. The electrical components were primarily purchased from Mouser and Digi-key while the PCB was purchased from OshPark. These companies were enriched by this project. Using spare components in the Cal Poly power electronics lab, the cost was able to be brought down as those components did not have to be purchased. No lab equipment needed to be purchased as the power supply and other testing equipment was provided in the power electronics lab.

If manufactured on a commercial basis

This product was not designed to be manufactured on a commercial basis. However, if it were it is estimated that none of these devices would sell per year. This is because of the size and
inefficiency of the board when compared to its competitors. Large electrical components were chosen for this product because they were easier to solder by hand. Furthermore, there is lots of spacing on the board to make the components more spread out and easier to solder. This contributes to electrical losses which would make this product inefficient when compared to similar products on the market. Large well established electronics companies would have a huge upper hand on three undergraduate students when it comes to bringing DC-DC converters to market. Given the fierce competition and the current specifications of the created current-source DC-DC converter, it would not be wise to manufacture this product on a commercial basis. This device was only intended to demonstrate a proof of concept.

**Environmental**

The metal materials needed to create the DC-DC converter were mined from the earth which caused pollution. The shipping of the components required fuel which also caused carbon dioxide to be released into the atmosphere. The construction and testing of the printed circuit board required power which may have not been generated with clean energy. The project as a whole created a carbon footprint which affected the environment.

**Manufacturability**

As the purpose of this project was to test a design in hardware, this product will not be manufactured on a large scale. The DC-DC converter was assembled on a printed circuit board and finding the correct components that were in stock was challenging.

**Sustainability**

The current-source DC-DC converter will not be winding up in a landfill as the project will remain in the power electronics lab. Further research and testing can be performed on the
board so it can be reused. Upgrades to the design can increase efficiency which would allow less energy to go to waste.

**Ethical**

When building and designing the product, the IEEE code of ethics was followed. We upheld the highest standards of integrity, responsible behavior, and ethical conduct in professional activities. The students involved in the project did not accept any bribes or break any laws to undermine the legal or moral integrity of the project.

**Health and Safety**

The input current should not exceed 1 Amp as the system is not designed for high current operation. In order to maintain safe operation, the voltage and current ratings for each component on the board should not be exceeded as well.

**Social and Political**

This project impacts the integrity of Professor Taufik’s current-source DC-DC converter design. He is a direct stakeholder as a great portion of his design was used to construct the product. Given that this design is intended to be used to power underwater communication systems, people who use those systems could also be stakeholders.

**Development**

This project required the DC-DC converter design to be implemented on a printed circuit board. Students involved in this project learned how to use Autodesk EAGLE in order to create the PCB layout and order it. This is a new skill that was learned in the course of the project.