Electrical Engineering Department  
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Senior Project Final Report  

MISO DC-DC Farmbot  
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Abstract

Making use of renewable energy directly from the location of production requires converting source power into usable power. The specific scope of this project focuses on the DC to DC conversion within a user friendly universal farmbot system. Since renewable sources vary widely in voltage and current, a wide input-range DC to DC converter is desired. Physical isolation, long lifespan, and adverse weather requires safe and reliable final product specifications. The goal of a very wide customer base drives the need for a product that does not require tinkering to get working, but to be usable out of the box for a vast majority of energy sources. This project designs, purely through simulation due to COVID-19 pandemic, a Universal Input Module (UIM) DC-DC converter, which acts as the first step from the energy source to the usable power bus. UIMs can be connected in parallel to effectively make a Multiple Input Single Output (MISO) system. The main component of conversion is a 4-switch buck-boost controller. Input filtering, output filtering, parallel function, and two theoretical renewable inputs are incorporated to give the simulated converter as realistic of a function as possible. The selection process for all main components, surrounding components, and equivalent simulation circuits is included. With use of LTSpice, the simulation results meet the customer’s specifications.
Chapter 1. Introduction

Electrical power can change in wattage, voltage, current, frequency, DC vs AC, phase count, and power factor. The most efficient form of generation, transmission, and use of power varies from application to application. For example, while most generation and transmission use AC power, many consumer products require DC power, which requires a device that converts AC voltage to DC voltage efficiently, generally known as rectifier [1]. The enabling technology that provides such an efficient conversion from one form of electrical power to another is known as power electronics.

Historically speaking, the defining goal of power electronics followed the same principle as it does today: maximizing financial efficiency. While early prototypes of electric generation and use required little to no transmission, the first step to a commercially available power grid in 1882 proved tough as the 57 km line, from the Bavarian Alps to Munich, came in at around 50% transmission efficiency. The first form of generation and distribution of electrical power was even worse as the first 80 customers ever served, on Pearl Street Manhattan, were supplied by six dynamos with 6% overall efficiency. These DC generators and lines sufficiently supplied short distance grids at low DC voltage level but were soon out-competed by high-voltage AC as line and transformer loss decreased with the higher voltages [2]. By 1902 a single power station, designed by Nikola Tesla and established by George Westinghouse, supplied an 11 kV three-phase AC line across 32km to Buffalo, producing a fifth of electricity in the United States [3]. Business was driving the need for more and more efficient forms of power use and there only seemed to be ever increasing opportunities for budding technology to play a role.

Power electronics of today follows the use of semiconductor devices as tools in increasing input to output power efficiency. The component categories fall under their association to AC and DC power: rectifier for AC to DC conversion, inverters for DC to AC conversion, DC-DC converters, and AC-AC converters. Efficiency depends on three areas of possible improvement: smarter real-time control of devices, device topology, and device technology [1]. For example, both a snubber circuit, a topology, and
higher quality MOSFETs can reduce switching losses, but the correct choice depends on the exact application at hand. As a secondary priority among businesses emerges, the environmental impacts of industry, power electronics asks the question of how to reduce emissions. Since renewable is the empowering answer among small scale investors, the change in power generation demands different forms of electrical conversion.

The main advantages of using renewable energy sources is that it is sustainable and low in pollution. Fossil fuels are finite resources that cannot be used indefinitely and cause pollution during combustion. Renewable energy such as solar, wind, hydropower, geothermal, solar photovoltaic etc. offers better environmental and economic benefits as they produce no greenhouse gases. As a result, there has been a significant demand for renewable resources in recent years. Countries like Denmark expect to be 100% fossil-free by 2050 [4]. With the shift in the energy paradigm from fossil-based resources to renewables in the past decades, power electronics has become more popular in increasing efficiency for renewable energy sources. The most emerging renewable energy sources (wind and photovoltaic) make use of power electronics technology in generation, grid integration, transmission, and end-user application. Figure 1.1 summarizes the broad picture of how power electronics is used to implement renewable sources. In this figure the power electronics block converts the DC output voltage from the renewable energy source such as solar panels to AC voltage which can be used directly by the load as well as fed back to the grid. For wind generators, power electronics may be used to regulate the varying AC output voltage due to the varying wind speed to the AC output voltage required by the load or grid.
Throughout the years many researchers have been carried out on ways to maximize energy collection from renewable resources. Maximum Power Point Tracking (MPPT) is one of the few common techniques used to maximize Photo-Voltaic (PV) systems output power before it gets delivered to the load. However, to efficiently harvest the energy from DC producing renewable sources, the system needs a converter to transform the voltage from the source to the appropriate level needed by the DC bus and other individual devices. The advantage of using a DC-DC converter over a linear regulator is the overall higher efficiency and their ability to process high power which makes them ideal for renewable energy applications. Relatively recent advancements in power electronics allow for affordable DC-DC power conversion, which allows for the use of renewables geographically separated from the grid in an affordable manner.

DC-DC converters come in two main forms: isolated versus non-isolated. The common non-isolated DC-DC converter topologies include Buck (step down), Boost (step up) and Buck-Boost (step up and step down). Often a system requires electrical isolation of output from the input. This is achieved by adding a transformer to the design. For such cases, isolated DC-DC converters such as Push-Pull, Flyback and Single Switch Forward can be used. Each topology has their own advantages and disadvantages based
on application. There are other topologies that further improve upon these designs by reducing switching losses with the use of soft switching techniques. The type of converter used depends on the design metrics, but there are always tradeoffs between cost, board space and efficiency.

One unique application of DC-DC converters calls for a way to combine multiple energy sources to power a single DC bus. Such a converter is called Multiple Input Single Output (MISO) DC-DC converter. In [5], [6], and [7], multiple well-known DC-DC topologies have been studied to determine which topology provides the most practical solution for the multiple input single output DC-DC converter.
Chapter 2. Background

Renewables meet the energy and environmental demands of the public and private sector in an economical way. Choices supporting sustainable options have ramped up over the past few decades, already reaching $155 billion yearly spending a decade ago [8]. Recent business practices show conscious decisions to purchase green power, both for morality and to improve “employee morale” [9]. Not all renewables are the same though, as theoretical research is helping identify the most viable sustainability options among those currently available on the market [10]. As the original investment to renewables is relatively small, it proves to be a uniquely attractive option among private investors. Affordability among an entire energy system looking to make use of renewable energies is paramount. Power conversion is necessary to bridge the gap between the morally driven and practical business opportunity.

To make use of renewables requires electrical conversion accommodating for low electrical inertia, physical isolation, and non-linear power production curves. Renewables generally do not follow the traditional expectations of steady output power. As a remedy to highly variable production, most opt to make use of multiple renewable energy sources at once, specifically wind and solar. Efficiently sourcing from two or more renewables requires a wide input range and max power point tracking. A viable system making use of renewable energy also requires batteries to provide “power balance,” even when connected to the grid [11]. Within systems isolated from the public grid, commonly called microgrids, the shortcomings of renewables become more apparent as no power alternatives exist. Research into rural microgrid planning shows the deeply economic process of producing electricity in physical isolation [12]. As is commonly concluded, the most economically viable option for physically isolated renewable energy systems include the use of a two input, wide input range, and battery connected DC-DC converter [13].

The type of DC-DC converter topology depends on the application of the overall circuit. Initial MISO prototype [14] by students at California Polytechnic University uses a full bridge topology. In a full bridge transformer, each input source uses a single primary winding thus minimizing the transformers
sizes. The overall circuit is also relatively small for the same output power compared to other isolated topologies. Another senior project [15] improved on the original design’s efficiency and lack of isolation by implementing a flyback converter instead of full bridge. A flyback converter uses only one switch and one winding per input which reduces cost and complexity of the control circuit. On the non-isolated converter side, a four switch buck boost design was implemented for a USB-Charger by another group of students [16]. The use of four switch buck boost gets rid of the negative polarity which is what one gets from a traditional buck boost circuit. This circuit is relatively simple compared to the isolated converters.

As mentioned earlier, the type of DC-DC converter topology depends on the applications and requirements. In cases where isolation of inputs and outputs are not needed, traditional non-isolated DC converters such as buck, boost, or buck boost can be used. This project focuses on the DC-DC converter application on a farmbot for a wide input range of 10V-80V from two renewable sources. Either a flyback or buck-boost converter can be used for the design. After comparing previous designs with the customer's recommendations, a simple OR diode configuration using four switch buck-boost converters is proposed for this project. There are two ways to implement OR diodes in a MISO converter [17]. One way is to connect each source to an energy source to an OR diode and use a converter. An alternative way is to implement a converter on each source followed by an OR diode which connects to the load. This project implements the second design to make equal use of all inputs by using a DC-DC converter per power source.

The objective of this project is therefore to design and build a multiple input single output DC-DC converter that will make use of two sources such as wind and solar. Each source will be interfaced as an input to their corresponding MISO converter. The topology used within the MISO converter is the 4-switch Buck-Boost topology. The output of these MISO converters is then combined to get a single DC output voltage to provide energy sufficient for small-scale farming application. OR diode configuration will be used to establish the common connection from each MISO converter. Hardware prototype of the MISO converter will be designed, constructed, and tested to evaluate its performance. Cost analysis of the converter will also be provided as part of the deliverables from this project.
Chapter 3. Design Requirements

The client for this project specifies the intended engineering specifications for the DC-DC converter. The converter is part of a bigger system that the client is working on as shown in Figure 3.1. This project focuses on the buck boost converter and the battery charging circuits. While the required input range and steady output voltage is required, most other specifications are open to flexibility. The design requires taking in two sources, or potentially more in the future with modular design, and converting them in parallel to a steady output voltage line. The client also wants the product to act as a reliable, long-lasting, somewhat universal DC-DC power converter.

Figure 3.1: Current architecture of overall system provided by client
Figure 3.2 shows the system's performance from an outside perspective. As the target customer will want a dependable power production as possible, the likely usage of this converter will take in multiple inputs of varying types. Multiple input types will require a wide input voltage range. The basic concept of power conversion will include a buck-boost topology such as the 4-switch buck-boost converter whose output is set at 24V.

Figure 3.3: Level 1 block diagram

Figure 3.2 displays the proposed level 0 block diagram of the DC-DC converter. The solar and wind sources will be simulated using power supplies. The battery system is made of Interstate DCM0035
35Ah battery. Maximum power point tracking (MPPT) boards will convert each input to the maximum possible power. These will be in line with the 4-switch buck-boost converter which will be the driving board for setting the output to 24V. The 4-switch buck boost should have input voltage ranging from 10V to 70V which would be the range provided by the renewable energy sources. The 4-switch buck boost converter will be chosen over the standard buck-boost due to the positive output-input transfer function that it provides, unlike the negative output voltage given by the traditional buck boost circuit. A Buck module with MPPT battery controller will also be used to maximize the output power delivered by the energy sources. The diodes from each converter path combine the energy from the multiple renewable energy sources to the single 24V DC output bus.

Table 3.1 summarizes the technical design requirements for this project along with their relevant reason or justification.

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<th>Need</th>
<th>Specification</th>
<th>Justification</th>
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<tr>
<td>Constant output power</td>
<td>120W at 24V</td>
<td>Variable source production should not mess up the customer’s use of power.</td>
</tr>
<tr>
<td>Multi-source and Variable Input</td>
<td>At least two wide range (10V-70V)</td>
<td>To not waste power production from off-site sources, the MISO must handle a wide range of input voltages.</td>
</tr>
<tr>
<td>DC output</td>
<td>&lt;1% AC ripple</td>
<td>System coupling requires steady state DC.</td>
</tr>
<tr>
<td>Standardized Shape</td>
<td>Limited components heights for stackable bricks</td>
<td>Uniform shape allows for easy transportation and systemic installation for wide agricultural use. Efficiency is of the utmost importance for system integration.</td>
</tr>
</tbody>
</table>

For this project, the system will have two inputs from solar and wind turbines with maximum power point tracking. The system will accept a wide input range of 10-70V and give a single output of 24V. The maximum rated output power is 120W. The efficiency of the buck boost converter must be greater than 94% at maximum rated output. The designed PCB must be single sided with four-six
mounting holes. All component heights shall be limited to less than 1.25 inches. The PCB dimensions must not exceed 3 inches by 5 inches to fit the existing platform. The module should cost less than $150 at a quantity of 100 modules. This includes electrical components, connectors, thermal interface materials and PCB.
Chapter 4. Design

Due to the current pandemic situation, the scope of this project has shifted and will focus only on the design and simulation of the Universal Input Module (UIM) and the functionality within the surrounding circuits. This chapter focuses on the design calculations for the module along with the complete bill of materials needed to build the printed circuit board.

The level 2 block diagram in Figure 4.1 displays the UIM with the main connected circuitry. LTSpice simulation will be conducted for a wind source, a solar source, standard DC-DC converter input filtering, the power stage using a 4-switch buck-boost, and standard DC-DC converter output filtering. Input filtering includes EMI filtering. An additional feature that is currently outside the scope of the project is the microcontroller for Maximum Power Point Tracker (MPPT). As an alternative to the microcontroller, controlling the MPPT could be done by adjusting a potentiometer at the output feedback loop of the power stage.

Figure 4.1: Level 2 block diagram
Design Calculations

To perform the design calculations for the proposed system, we will need to have a set of operating parameters. The following lists the provided parameter values:

- **Switching Frequency \( f_{sw} \)**
  
  We specify a moderate switching frequency in given values but recalculate the frequency when selecting a standard \( R_f \) value.

- **Peak to peak Inductor Current Ripple \( I_{L_{ppmaxPerc}} \)**
  
  This is typically given in percentage of the maximum average inductor current. A range of 30%-40% is the widely accepted industry normal range to start the design.

- **Peak to peak Input Voltage Ripple \( V_{i_{ppmaxPerc}} \)**
This is also typically given in terms of maximum percentage of the actual average input voltage. Percentage of 5% or less is quite common for power supplies.

- **Peak to peak Output Voltage Ripple Vout_pp**
  
The customer specifies this requirement. The value is typically given in maximum percent peak to peak ripple with respect to the actual average output voltage value.

- **Sensing Resistor Margin_Rlsense**
  
The LT8705 datasheet page 23 explains and recommends a proper value for this.

- **Minimum peak to peak Inductor Current Ripple in Buck Mode Ilpp_minbuck**
  
The LT8705 datasheet page 23 also describes and suggests a proper value for this specification.

- **Feedback Resistor Rfb_out2**
  
The customer recommends the resistor value for the design.

- **Derating Consideration**
  
The customer provides the derating engineering requirement of 70% for capacitor voltage, capacitor ripple current, inductor saturation current, transistor voltage, and diode voltage.

The following summarizes the given design parameters:

- $I_{o\_min} = 0.5\ A$
- $I_{o\_max} = 5\ A$
- $V_{in\_min} = 10\ V$
- $V_{in\_max} = 70\ V$
- $V_{in\_nom} = 30\ V$
- $V_{out} = 24\ V$
- $f_{sw} = 200000\ Hz$
- $R_{ppmaxPerc} = 0.3$
- $V_{i\_ppmaxPerc} = 0.05$
- $V_{out\_pp} = 0.25\ V$
- $Margin_{Rlsense} = 0.3$
- $Ilpp\_minbuck = 0.1$
- $Rfb\_out2 = 1000\ \Omega$
- $derating = 1.7$

Furthermore, for the Gate Resistors (R_TG1, R_BG2, R_TG2), the LT8705 datasheet page 27 recommends using between 1Ω and 10Ω resistors on the gate drive pins to dampen ringing. For this design, 2Ω resistors are selected to keep drive loss low.

Inductor Sense Resistor (Rs_L)
Page 7 of the LT8705 datasheet provides a figure as replicated in Figure 4.3 to calculate the maximum sense voltage in boost mode depending on the duty cycle. With a duty cycle of 58.3%, the maximum sense voltage is 9.8mV, which is used in later calculations.

“RSENSE Selection and Maximum Current” section in the LT8705 datasheet starts on page 22 and explains all required calculations. Inductor current ripple in Buck mode \( I_{\text{rippleBUCKpercent}} \) and the MarginRsense are given as well in the same section.

The final value of 5m\( \Omega \) was chosen for the RSENSE resistor.

\[
DC_{maxM3\text{boost}} = \left( 1 - \frac{V_{\text{in.min}}}{V_{\text{out}}} \right) = 0.5833
\]

From Graph: \( V_{\text{rsenseMAXboostMAX}} = 0.098 \text{ V} \)

Figure 4.3: RSENSE graph and equations.
Next is the Inductor Current Sense Filtering which consists of several components R_L1, R_L2, CL1, CL2. Figure 13 on page 34 of the LT8705 datasheet provides the recommended filtering layout and values.

The main Inductor (L) calculations follow the equations listed in the LT8705 datasheet, starting on page 24. In summary:

- The maximum value of L_{min1\_boost}, L_{min2\_boost}, and L_{min1\_buck} is 10.6\mu H. We chose the commercially available 15\mu H inductor that allows for a margin of error.
- The maximum value of I_{L\_maxboost} and I_{L\_maxbuck}, which includes the 70% customer specified derating, is 22A. The selected inductor has a saturation current of 51.6A, which is above the required 22A.
- The following shows the calculations:

\[
I_{L\_rippleMAXboost} := \frac{V_{out} \cdot I_{o\_max}}{V_{min} \cdot \left( \frac{1}{I_{L\_ppmaxperc}} - 0.5 \right)} = 4.2353 \text{ A}
\]

\[
R_{senseMAXboost} := \frac{2 \cdot V_{senseMAXboostMAX} \cdot V_{min}}{\left(2 \cdot I_{o\_max} \cdot V_{out}\right) + \left(I_{L\_rippleMAXboost} \cdot V_{min}\right)} = 0.0069 \Omega
\]

\[
I_{L\_rippleBUCKpercent} := 0.1
\]

\[
I_{L\_rippleMINbuck} := \frac{I_{o\_max}}{\left( \frac{1}{I_{L\_rippleBUCKpercent}} - 0.5 \right)} = 0.5263 \text{ A}
\]

\[
R_{senseMAXbuck} := \frac{2 \cdot 0.086 \text{ V}}{\left(2 \cdot I_{o\_max}\right) - I_{L\_rippleMINbuck}} = 0.0182 \Omega
\]

\[
MarginR_{sense} := 0.3
\]

\[
R_{s\_L} := \min\left(R_{senseMAXboost}, R_{senseMAXbuck}\right) \cdot (1 - MarginR_{sense}) = 0.0049 \Omega
\]

\[
R_{s\_L\_used} := 0.005 \Omega
\]
Feedback output resistors (Rfb\_out1, Rfb\_out2) were selected based on the equation provided in the LT8705 datasheet page 29. Approximate resistances are calculated, and then commercially available standard resistors are chosen. With these standard values, the nominal output voltage equals 24.17V.

\[ P_{o\_max} = V_{out} \cdot I_{o\_max} = 120 \text{ W} \]
\[ I_{in\_max} = \frac{P_{o\_max}}{V_{in\_min}} = 12 \text{ A} \]
\[ DC_{\_max\_buck} = 1 - \frac{V_{out}}{V_{in\_max}} = 0.6571 \]

\[ L_{min1\_boost} = \frac{2 \cdot f_{sw} \cdot \left( V_{sense} \cdot MAX_{boost} \cdot MAX - \left( I_{o\_max} \cdot V_{out} \right) \right)}{R_{s\_L\_used}} \]
\[ L_{min1\_boost} = \left( 1.9386 \cdot 10^{-6} \right) \text{ H} \]

\[ L_{min2\_boost} = \frac{V_{out} - \left( V_{in\_min} \cdot V_{out} \right)}{V_{out} - V_{in\_min}} \cdot R_{s\_L\_used} \]
\[ L_{min2\_boost} = \left( 2.1649 \cdot 10^{-6} \right) \text{ H} \]

\[ L_{min\_buck} = \left( V_{in\_max} \right) \cdot \left( 1 - \frac{V_{out}}{V_{in\_max} - V_{out}} \right) \cdot \frac{R_{s\_L\_used}}{0.08 V \cdot f_{sw}} \]
\[ L_{min\_buck} = \left( 1.057 \cdot 10^{-5} \right) \text{ H} \]

\[ L_{used} = 15 \cdot 10^{-6} \text{ H} \]

\[ I_{l\_max\_boost} = \left( I_{o\_max} \cdot \frac{V_{out}}{V_{in\_min}} + \left( V_{in\_min} \cdot \frac{DC_{\_max\_M3\_boost}}{2 \cdot L_{used} \cdot f_{sw}} \right) \right) \cdot \text{derating} = 22.0698 \text{ A} \]

\[ I_{l\_max\_buck} = \left( I_{o\_max} + \left( V_{out} \cdot DC_{\_max\_buck} \right) \right) \cdot \text{derating} = 13.0145 \text{ A} \]

Feedback output resistors (Rfb\_out1, Rfb\_out2) were selected based on the equation provided in the LT8705 datasheet page 29. Approximate resistances are calculated, and then commercially available standard resistors are chosen. With these standard values, the nominal output voltage equals 24.17V.

\[ R_{fb\_out1} = R_{fb\_out2} \cdot \left( \frac{V_{out}}{1.207 V} - 1 \right) = \left( 1.8884 \cdot 10^4 \right) \Omega \]

\[ R_{fb\_out1} = 21500 \Omega \]

\[ R_{fb\_out2} = 1130 \Omega \]

The Boost Diodes and resistor (DB1, DB2, Rb, Cb1, Cb2) requires a one-way charge flow to maintain the gate voltages. We considered the following:

- Using the “Topside MOSFET Driver Supply” section of the LT8705 datasheet starting on page 28 which recommends 0.1μF to 0.47μF for most applications, we decided to use the standard capacitor value of 0.22μF.
Additionally, page 29 of the same datasheet recommends a resistor up to 5Ω to be placed in series with the diodes. The resistor reduces surge current on the diodes.

The next component is the Switch Enable Pullup Resistor (Rswen). This is a resistor that connects the SWEN pin to the LDO pin to enable switching. The datasheet states that a commonly used resistance for a pull-up resistance is 100kΩ.

Input voltage lockout resistors (Rlock_in1, Rlock_in2) are next to determine. These resistors serve as a voltage divider for the shutdown pin, typically chosen as 33kΩ and 10kΩ resistors. These values correspond to the controller shutting down and turning on at input voltages of 5.3V and 5.1V, respectively. The resistor values must also be selected to fall under the maximum allowable SHDN pin voltage. 33kΩ and 10kΩ set the allowable pin voltage between 2.33V to 16.3V, which is well within the functional range of 1.234V and 30V.

\[
R_{lock\_in1} = 33000 \ \Omega \quad R_{lock\_in2} = 10000 \ \Omega
\]

\[
V_{in\_chip\_Off\_falling} = \frac{(R_{lock\_in1} \cdot 1.184)}{R_{lock\_in2}} + 1.184 = 5.0912
\]

\[
V_{in\_chip\_Off\_rising} = V_{in\_chip\_Off\_falling} \cdot \frac{1.234}{1.184} = 5.3062
\]

Another component is the loop compensation (Rc, Cc1, Cc2). Page 33 of the datasheet includes a brief paragraph on loop compensation. After simulation testing, the output voltage ripple performed best at a resistor Rc of 20kΩ. The capacitor values did not adjust the output voltage ripple greatly; thus, the recommended values are kept the same.

To set the switching frequency, the Frequency Controlling Resistor (Rt) needs to be chosen properly. This is the resistor which is connected from the Rt pin to ground. We did the calculation for Rt first, pick a standard Rt value next, and then recalculate the actual switching frequency. The following shows the calculations.
Input Ripple Reduction Capacitor (Cin) is needed to reduce the peak to peak input voltage ripple. Page 136 of the EE527 textbook provides the following equation. Plotting input capacitance vs. Input voltage as shown in Figure 4.4 displays the peak input capacitance required at just over 3μF.

\[
R_t := \left( \left( \frac{43750000 \text{ Hz}}{f_{sw}} \right) - 1 \right) \cdot 1000 \Omega = (2.1775 \cdot 10^5) \Omega
\]

\[
R_t = 220000 \Omega
\]

\[
f_{sw} := \frac{43750000 \text{ Hz}}{\frac{R_t}{1000 \Omega} + 1} = (1.9796 \cdot 10^5) \frac{1}{s}
\]

\[
C_{in} := P_{o_{max}} \cdot \frac{(V_i V - V_{out})}{V_{i_{pmpmax}Pe_{c} \cdot f_{sw} \cdot (V_i)^3}} \cdot V^2
\]

Figure 4.4: Input Capacitance vs Input Voltage

Peak to peak Output Voltage Ripple Reduction with Output Capacitor (Co1). Reducing output voltage ripple requires capacitance to store bulk charge. Simulation of controller at worst performing input, 10V in and 5A out, yielded an electrolytic minimum capacitance around 150μF. This was a higher value than what the calculations yielded, as shown below to be 14μF.
Another needed capacitor is the Output Switching Spikes Reduction capacitor (C_{o2}). Steady-state output voltage contains ripples with switching spikes. A capacitor in parallel at a minimum of around 50\mu F yielded good transient steady state settling time in simulations.

Bypass Capacitors (C_{vcc}, C_{LDO}, C_{vi}) as described on page 32 of the LT8705 datasheet requires a minimum of 4.7\mu F ceramic capacitance from INTVCC and GATEVCC to ground. Pages 11 and 12 list LDO33 and Vin pins as requiring bypass capacitors. The commonly used value of 1\mu F is used.

Next, the Soft-Start Capacitor (C_{ss}) is a capacitor connected from the SS pin to ground to control the speed of voltage ramp on startup. While 5nF was used for faster simulations, page 15 of the LT8705 datasheet recommends a minimum of 100nF.

Lastly, switches (MT1, MB1, MB3, MT2) will be 4 MOSFET switches that are rated based on minimum voltage and current ratings. Page 138 and 139 of the EE527 textbook list all the following equations. Minimum and maximum duty cycles of 0 and 1 are used for worst case scenarios.

\[ D_{min} := 0 \quad D_{max} := 1 \]

\[ V_{sw\_MT1B1} := V_{in\_max} \cdot \text{derating} = 119 \text{ V} \]

\[ V_{sw\_m3} := V_{out} \cdot \text{derating} = 40.8 \text{ V} \]

\[ I_{sw\_MT1} := \frac{P_{o\_max}}{V_{in\_min}} = 12 \text{ A} \]

\[ I_{sw\_MB1} := (1 - D_{min}) \cdot I_{o\_max} = 5 \text{ A} \]

\[ I_{sw\_MT2} := D_{max} \cdot I_{o\_max} = 5 \text{ A} \]

\[ I_{sw\_MB2} := I_{o\_max} = 5 \text{ A} \]
Chapter 5. Simulation Results and Analysis

Simulation Tool Selection

All simulations are done using LTspice. At no cost to users, LTspice allows free and easy use by the current design team and all future engineers. Familiarity of the software among team members makes the software the first choice among electronic simulations. The software also allows easy compatibility of components, specifically the automatically included LT8705A controller, and gives confidence in the credibility of the simulated results. In addition, it does not require subscription or payment which contributes towards the goal of the project to be an open source project.

Simulation Setup

The first simulation includes a basic controller functionality circuit schematic. This is the standard circuitry around the controller with a single input and output capacitor with an ideal input source of range 10V to 70V and load ranging from 0.5A to 5A. This is included in the first level since the circuit cannot function without bulk charge storage on input and output capacitors. No equivalent series resistance (ESR) values are added during the ideal testing.
The controller is designed to be in use with renewable energy sources, specifically wind turbine and solar panel inputs. A wind turbine and solar panel equivalent circuit input voltage and current into the controller. Each equivalent circuit is input to the controller and simulated separately.

Figure 5.2 and 5.3 show the design approach to each equivalent circuit. The calculation of Figure 5.3 is used with a guessed N value, usually 10-100, and then tested with a voltage source on the output. The value of N is changed until the curve fits approximately a realistic PV solar panel IV curve. The specific values are used to give realistic input sources for a 120W max output converter. Table 5.1, at the end of this chapter, shows load currents at 3A and 1.5A for turbine and solar inputs, respectively. The low load currents are necessary to allow production of enough power by the equivalent input circuits. If the
circuit wants to be tested at full load with solar and turbine inputs, then much larger solar and turbine sources will need to be used.

Realistic functionality requires taking in two or more sources at once. Controllers are diodes connected together in parallel to accommodate multiple sources. For the first parallel simulation, the inputs are ideal. The first input is 10V. The second input is delayed by 5ms and then takes 5ms to get up to 70V. Testing a delayed input can show controllers function both separately and together. Figure 5.6 of
the fully functional circuit shares the same diode connections as the ideal parallel layout. The following model is used as an equivalent of the SM74611KTTR low forward-voltage diode.

```
.model MyDiode D(Tpk=15,vpk=30,Ron=3.25m,Roff=93.3Meg,Vrev=28)
```

The filtering simulations are designed to help meet specifications while taking into account major non-idealities. The engineering specifications require 250mV maximum peak to peak output voltage ripple, and -40dB filtering of the input current. The input filter adds \( Li \) and \( Ci2 \) in parallel within the input loop. Within Figure 5.4, the added 4.7\( \mu \)H inductor and 150nF capacitor add a notch at the switching frequency of the controller. Simulation setup of the output filter adds \( Co2 \) within the output loop. Non-ideal ESR values of 250m\( \Omega \) for \( Ci \), 1.6m\( \Omega \) for \( Li \), and 25m\( \Omega \) for \( Co1 \) are added to the component definitions.

![Figure 5.4: Circuit and frequency response to find input filter inductor and capacitor values.](image1)

Figure 5.4: Circuit and frequency response to find input filter inductor and capacitor values.

![Figure 5.5: Input and output filter schematic](image2)

Figure 5.5: Input and output filter schematic
The final circuit is the full functionality circuit that employs all the specifications mentioned above. It adds the basic circuit of Figure 5.1 with the filters of Figure 5.5, the input sources of Figure 5.2 and 5.3, in parallel with the diode model mentioned previously.

Figure 5.6: Full functionality simulation set up

Simulation Results

Tabulated results are summed up in Table 5.1 at the end of this chapter. The table includes input voltage, output current, output voltage ripple, input current attenuation in dB, and efficiency all obtained from the waveforms.
Basic Controller

The peak to peak output voltage ripple is 71.6mV at steady state. Under ideal conditions, the basic circuit does not need any extra output filtering.

Figure 5.7: Steady state output voltage and input current waveforms of basic circuit at 10V input and 5A load

Figure 5.8 shows input power oscillating greatly, even during steady state. Since input voltage is constant, this equates to very high oscillations in input current. Output voltage and power rise as expected.
Figure 5.9: Output voltage waveforms at 0.5A and 5A loads.

Figure 5.10: Output voltage waveform at minimum, nominal, and maximum input voltage with 5A load.

Since this is a commercially available product, the line and load regulation should be close to zero, which matches the simulation shown in Figure 5.9 and 5.10.
With the ideal basic circuit, the frequency of the input current does not meet the desired -40dB attenuation. The highest points correspond to switching frequency and harmonics of switching frequency. -10dB is 30dB away from engineering specs, while many harmonics are also above.

**Turbine and Solar Input Equivalents**

Since the equivalent sources are not tested at full load, many specs are not graphed or recorded. Fluctuations of inputs approximately change inversely, which matches the equivalent curves of Figure 5.2 and 5.3. This simulation is mostly to verify the equivalent circuit functions as expected. Some other values are in Table 5.1 at the end of this chapter.
Parallel Controllers

Simulations of parallel connected controllers is paramount to verify the function of the converter in the larger system as a whole. Figure 5.14 shows diodes switching depending on which input has higher output voltage. Delaying the 70V input by 5ms delayed the secondary output reaching steady state by approximately 8ms. Before this time, only D1 is on. During steady state both output voltages are close to each other, but with the 70V input pushing more current through its output diode D2 of Figure 5.14.
Previously, the output diodes were not selected. Older simulations showed significant power loss due to forward-voltage diode drop. The SM74611KTTR acts as a great option for a low forward-voltage diode. The data sheet lists power loss at 8A to be 208mW. With lower output current and a non-linear power loss curve, the expected power loss is about 100mW. Simulations yielded total diode power loss of 78mW. Either way, this allows for a much higher efficiency when controllers are connected in parallel.

![Figure 5.14: Parallel controller output voltages before diodes and output diode currents](image)

Figure 5.14: Parallel controller output voltages before diodes and output diode currents

![Figure 5.15: Parallel controller total output voltage and input currents of ideal parallel controllers](image)

Figure 5.15: Parallel controller total output voltage and input currents of ideal parallel controllers

Figure 5.15 shows very high spikes, especially at steady state of the input current from the 70V source. Without input filtering, parallel connected controllers do not meet EMI. Figures 5.16 and 5.17 show more clearly the frequency domain of the input current.
The main function of simulating non-ideal capacitors and adding filters is to check if input current can reach -40dB attenuation while output voltage remains below 250mV peak to peak. Figure 5.19 shows the filter did not quite meet the desired specification, yet the approach used is likely correct. While the basic circuit met the maximum input voltage peak-to-peak specification, adding the input filter
increased it. Through simulation, minimum ceramic capacitance came out to be $50\mu F$. Capacitance greatly below would not meet the maximum output voltage ripple of $250\text{mV}$. $47\mu F$ is used as a common component value. Figure 5.18 displays the transient as well as low current and voltage ripple.

![Figure 5.18: Output voltage and input current of controller with non-ideal filters](image)

![Figure 5.19: Steady state input current FFT of controller with non-ideal filters](image)

**Full Functionality**

As seen in Figure 5.20, both output voltages rise very smoothly. Since both voltages are very close to each other before the diodes, as seen in Figure 5.21, the diodes end up sharing the total output
current. Diode current is proportional to output voltage right before that diode; therefore, the turbine output voltage is always higher than solar output voltage during steady state.

Figure 5.20: Output voltages and diode currents of Full Circuit

Figure 5.21: Output voltages before and after diodes of Full Circuit

Figure 5.21 shows the difference between each output voltage before the diode and then the voltage after the diode. At steady state, there is a 6mV to 9mV drop across the diodes. This follows somewhat closely to the expected drop of 3.25mV.
Inverse proportionality between input voltage and current remains the same when each source is connected in parallel, as seen in Figure 5.22. To note, the input values do not reach steady state until around 200ns after the output voltage reaches steady state.

Figures 5.23 and 5.24 show the high frequency response seen on the input current. Even though this meets the engineering specifications of -40dB, the input sources output far below 70V, around 21V at steady state. As input voltage increases, high frequency input current will rise.
The most basic circuit met the output voltage ripple specification without any additions. In previous versions of the input and output capacitors the basic circuit outputs too much voltage ripple, but under the finalized electrolytic capacitor values the output ripple turned out to be quite low. This of
course changed when trying to accommodate the -40dB current input parameter. While a 47µF was used as the secondary output capacitor, a larger one can be used to further lower the output voltage.

The line and load regulation were very close to zero. In hindsight, this should have been expected since the control stage tightly controls the output. A 4-switch buck-boost is meant to be used along the full input range.

Early versions of the equivalent input circuits proved very unstable before steady state. Only after realizing that the output resistor was drawing too much power for the source to provide, did the transient slopes start to look more ideal. The wide input range clashes with the constraint of the somewhat low maximum output power. This will be discussed more in the next Chapter.

Overall, the fully functional circuit performed much better than expected as the input voltages and currents remained fairly stable before steady state. Looking at Table 5.1, the current layout would likely suffice for in field use but could take adjustments in the input and output filter. A larger non-electrolytic output capacitor will further decrease the final steady state output voltage. A Pi or two-stage filter could work better on the input, but simulations of those filters did not see a significant increase in performance.
Chapter 6. Conclusion

This project explored the design and simulation of a customer specified DC-DC converter for multiple input single output application. The MISO Farmbot offers universal input from multiple sources at once and outputs steady energy. The goal of the project was to design an efficient converter for farming application. The designed converter can take two inputs from renewable sources between the specified range of 10V-70V. The output voltage had less than 1% AC ripple which met the customer specifications. While the components were picked for durability, electrolytic filter capacitors did not meet the specifications of lasting 20+ years.

The originally specified switching frequency attenuation turned out to be derived from the output voltage instead of the input current. The currently designed input filter over accommodates the specification of less than 40dB attenuation as it was able to attenuate to 100dB at switching frequency. However, it lacks in-built dampening which could be a potential problem depending on the application of the circuit. While not strictly a conflict with the original engineering specifications, damping circuitry could help with future proofing against unseen applications.

While the designed circuit met the specifications, the specifications intentionally limit the scope of the project to keep goals manageable. Placing three or converters in parallel may have consequences not shared by two converters. The two input source equivalents did not vary greatly. Taking into account other sources could help expand the use of the final product. More simulations would help fill in the realistic holes left by the self-designated scope.

The maximum output power conflicts with the input voltage range. While such a large voltage range increases the “universality” of such a converter, realistically the only range required is the maximum power point for each input source. Simulations showed typical solar panel and turbine input sources would likely never use even half the input voltage range. This take on the unnecessity of the input voltage range may be due to the project scope but meeting the requirements for typical input application would likely also meet almost all applications, if given enough error room.
The final step for actual production is conflict between lowering the price tag and meeting unassigned engineering specifications. The product is supposed to last for 20 years, yet most parts were not selected with critical attention to this specification as the exact way to go about finding the right parameter was not practiced at the time. Durability, scale, and manufacturing will serve as good stepping points for any group looking to apply the final design into hardware.

Lastly, due to the unfortunate COVID-19 pandemic, the initial plan of constructing a hardware prototype for the proposed design had to be put off. Campus shutdown during the pandemic included closing all access to labs on campus. As all of the lab equipment and tools necessary for building and testing a hardware prototype are in the power electronics lab, it was decided that this project therefore must be done via simulation study only. We definitely hope that when everything goes back to normal, another senior project group will take on this project to complete the hardware prototyping and testing of the design.
References

A. Final Schematic
B. Project Schedule

Winter 2020

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Winter 2020:
- Review & Literature Survey:
  - Research Any Previous Work
  - List References
  - Finalize Design Goals
- Design:
  - Level 0, 1, 2, Block Diagrams
  - Design, Calculations, Component Selections, Schematics and Simulation (if applicable)
- Component Selections and Purchase:
  - Search for Components
  - Bill of Materials and Board Layout (if applicable)
  - Order and Acquire Components
- Report Writing:
  - Chapter 1
  - Chapter 2
  - Chapter 3

Spring 2020:
- Design (For Chapter 4):
  - Design Equations
  - Component Selections
  - Circuit or System Design
- Computer Simulation (For Chapter 5):
  - Simulation Setup
  - Simulation Results
  - Data/Results Analysis
- Report Writing:
  - Chapter 4
  - Chapter 5
  - Chapter 6
  - Final Report Submission

Assignment Due symbols are shown at the bottom of each section.
## C. Bill of Materials

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Total: 42.32
D. Analysis of Senior Project Design

Project Title: MISO DC/DC Farmbot

Students: Astha Adhikari, Brian Armijo, Quyen Nguyen

Advisor: Dr. Taufik

1. Summary of Functional Requirements

The MISO Farmbot is a DC to DC power converter with a universal input that functions in isolation. The contained component includes a multi-input stage, a power conversion stage, a control stage, and an information relay stage. The device will function without any connection to the grid and will handle quick switching between inputs via parallel diodes. The input range will contain the expected voltage and current of renewable energy sources while the output is specified by the customer. The main purpose of the MISO Farmbot is to allow use of renewable energy sources independent of the grid.

2. Primary Constraints

Most technical constraints fall under electrical specifications. The Farmbot must take an input of 10V - 70V, and output 24V at a max power rating of 120W. Storing unused power in batteries allows long term use of generated energy. To efficiently deliver dependable energy conversion, the device must handle the full range of natural occurring weather conditions while maintaining a price tag at around $150.

3. Economic

(a) Human Capital: The Farmbot will create engineering, technician, and customer service jobs surrounding the small-scale energy conversion industry. Enabling private customers and
businesses to flourish will help smaller communities gain a foothold in financial and renewable markets.

(b) Financial Capital: This product’s price tag allows an almost limitless market for any rural customers looking to make the most of renewable energy sources. A small part of buck is passed from those installing energy production to the seller of this Farmbot. The rest of the payoff goes to the customer as this power converter cuts out a lot of unnecessary grid-tied infrastructure.

(c) Natural Capital: Electronic devices do not recycle well, but the surrounding mechanical containment will scrap into standard reusability establishments. Minimizing material will come naturally by maximizing efficiency of device cost and power conversion.

(d) Cost and Timing: The Farmbot DC/DC converter will cost $150 at a quantity of 100 modules sold. This price tag and sales magnitude will come within 5 years of device release. The prototype is expected to be complete by May 2020. A commercially available version will come after a year of testing.

4. **If manufactured on a commercial basis:**

   (a) Estimated Number of devices first year: 100-300 units
   (b) Estimated Number of devices at 2-5 years: 2000-10000 units
   (c) Estimated Number of devices after 5 years: 100k-200k units
   (d) Estimated manufacturing cost for each device: $45
   (e) Estimated purchase price for each for each unit: $150
   (f) Estimated profit 1st year, 2-5 years, and 5+ years: $15,000, $450,000, $11 million
   (g) Estimated Cost for User to operate devices: Ideally $0, subject to repairs
5. **Environmental**

The main environmental impact will come from the highly integrated electronic components ending up in landfills at the end of the device lifetime. Minimizing non-recyclable materials will help lower the negative material impact on the environment.

Electronic components mix Silicon and metal which ultimately come from mining practices. The silicon specifically comes from gravel, is isolated in an arc furnace with a reduction process, then finally cooled and crushed with use of slag. While the environmental impact of all this is significant, each Farmbot module uses a physically small amount of material.

The contained device will not directly affect animals. Renewable energy production can make a very small negative impact on the environment, but the alternative to renewable sources is much more costly to species life.

5. **Manufacturability**

Manufacturing will happen in a 2-stage process: electronic compilation and physical construction. The Farmbot requires a period between electronic and physical production for testing. A device that meets electronic standards will continue to mechanical containment and finally physical testing.

6. **Sustainability**

The Farmbot must handle the full range of environmental conditions. Without secure containment around the device reliability cannot be guaranteed. A universal customer requires all temperatures, precipitation, and minor physical perturbations. Long term protection from the environment is most challenging at the connection between the device and the outside sources. Secure and watertight connections are needed.
The Farmbot mainly cuts out the extensive wiring required for alternative power setups. The device attains minimal material while offsetting bulking electronics.

At the current target market, the input range does not go above a voltage and current threshold expected from private energy production. While more costly, an industry viable DC/DC converter would handle one to two magnitudes higher of input. At the moment the target design is attempting to maximize the relatively efficient customer market.

A magnitude of higher possible input will increase the cost while making relatively low power input less efficient. Larger sub circuits, such as controller and RLC components, will mean a higher price tag for production and the customer. To reasonably accommodate industry would mean lowering the efficiency of private users. At the time it is very inefficient to try to meet both target customers with the same device.

7. **Ethical**

The dangers of this product mainly come from the high-power levels incoming, in storage, and outgoing from the device. Directly, the Farmbot has the potential to give off lethal amounts of current. Indirectly, the electrical levels have the means to spark outside the device, which can start fires or harm surrounding components. Financially, a power converter must remain safely functioning to keep all surrounding electronic equipment from breaking.

8. **Health and Safety**

Private users rarely have the financial means to replace expensive electronic equipment, therefore the Farmbot manufacturing process must take into account safety measures to avoid sending out incorrect power. Many stages of a DC/DC converter contain safety levers to stop function if the circuit malfunctions, including the controller containing both an input and output current sensing stage. Design
will also include tertiary safety measures to ensure disaster will not come if the device does not function properly.

As students, this group project must contain a large amount of discipline in working towards commercial standards. With help from advisors, the Farmbot design, simulation, and build will contain many levels of checking to ensure no major flaws remain. We hope to work with each other and others to ensure safety and reliability.

9. **Social and Political**

Thankfully, Cal Poly’s community, and California as a whole, welcome the use of renewable energy positively. Enabling individual empowerment to make use of solar and turbine energy production is at the forefront of the design team, the advisors, and many of the customers. The social agreement in the use of something such as a Farmbot will only fail if safety or reliability becomes an issue.

The surrounding political environment mirrors the social atmosphere in wanting to make the most of renewable energy sources. While many industry and private experts are unsure of the full scope of the use of small-scale renewable, the Farmbot will fill in the gap that is left between grid-tied private properties and rural environments.