

MULTIPLE INPUT SINGLE OUTPUT CONVERTER WITH UNEVEN LOAD
SHARING CONTROL FOR IMPROVED SYSTEM EFFICIENCY

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical Engineering

by
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June 2020

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ABSTRACT

Multiple Input Single Output Converter with Uneven Load Sharing Control

for Improved System Efficiency

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This paper presents the development and study of multiple-input single-output converter (MISO) for the DC House project that utilizes a controller to maximize the overall converter's efficiency. The premise of this thesis is to create uneven load current sharing between the converters at different loading conditions in order to maximize the efficiency of the overall MISO converter. The goal is to find a proper ratio of current from each converter to the total load current of the MISO system to achieve the greatest efficiency. The Arduino microcontroller is implemented to achieve this goal. The design and operation of the MISO converter with the proposed controller will be explained in this paper. The design and operation of the converter was tested and verified through simulation in LTSpice in addition to hardware implementation. Different ratios of current from each converter were used to fully test the MISO converter. For the 5A and 6A load current, the maximum efficiencies were reached with the 70% / 30% ratio case, with efficiencies of 94.91% and 95.07%, respectively. For 7A load current, the maximum efficiency was reached with the 60% / 40% ratio case, with an efficiency of 94.59%. The results were then compared with those obtained from the equal current sharing cases. For the cases tested, the efficiency of the unequal current sharing outperforms that obtained from the equal current sharing method.

Keywords: Parallel, DC-DC Converter, Power Electronics, Buck, Multiple Input Single
Output

ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. Taufik for inspiring my interest in power electronics. Your enthusiasm and immense knowledge in power electronics has made me enjoy EE even more. You are one of the funniest, most down-to-earth, and smartest professors that I know. Never stop telling your ghost and college stories to your students! Those were some of the highlights of my days when I was in your power electronics classes! Again, thank you so much for your guidance, patience, and motivation in these past few years.

Thank you to Sabrinna Tan and Patricia Liu for coming into my life! You guys helped me get through this tough year and I definitely wouldn't have been able to do it without our one bean cell that we share! Thanks for all the love and support y'all brought into my life. Let's continue our one-million-hour long Zoom calls forever, even when Sab moves to Colorado! Also, don't forget that we promised Hawaii!

Thank you to Kenny Nguyen, my thesis partner, who supported me immensely throughout this past school year. Thanks for understanding the stress I felt throughout the school year and being there for me. Also, thanks for being just a great person overall. I can't wait to see what you and your genius brain accomplish in the future.

Last but not least, I would like to thank the most important people in my life. Thank you to my family: my dad, Chris, my mom, Jennet, my older sister, Jocelyn, and my younger sister, Kaitlyn. I definitely would not be where I am today without you guys, nor completed my thesis without your support and advice. Thank you guys for pushing me, your encouragement, and ultimately, unconditional love, to help me achieve my Master's degree in EE.

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1. INTRODUCTION

Since the development of electricity, Alternating Current (AC) has been the most predominant form of electricity used in the world to transmit and distribute electrical power from generating stations to loads. AC electricity offers advantages which make them more preferred over the Direct Current (DC) counterpart. One major advantage relates to the convenience in transforming AC voltage from one level to another level via a transformer. This allows for efficient transmission of power from one location to another resulting in a complete transformation of the power systems to AC. However, with recent advances in power electronics it has become possible nowadays to perform the same voltage transformation on DC voltages.

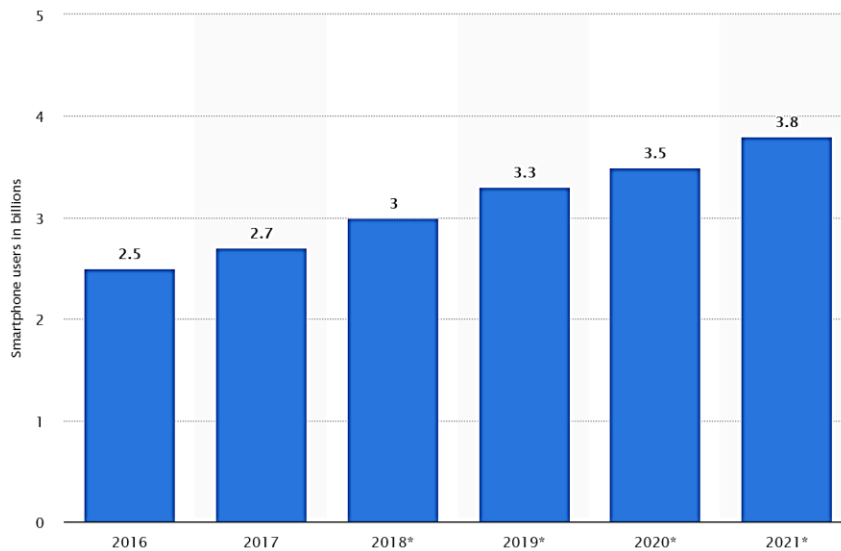


Figure 1-1: Number of smartphone users worldwide from 2016 to 2021 [1].

As electronics technology is advancing, the number of DC devices has been increasing. Smartphone users worldwide for example has grown from 2.5 billion in 2016 to 3.3 billion in 2019, and is projected to continue to grow to 3.8 billion in 2021, as shown in Figure 1-1 [1]. The continuing increase in DC devices poses a challenge for AC electrical systems since this would imply the need for lossy AC to DC conversion or rectifier. Coupled with the increasing DC energy sources such as solar panels and fuel cells, interest in DC has returned.

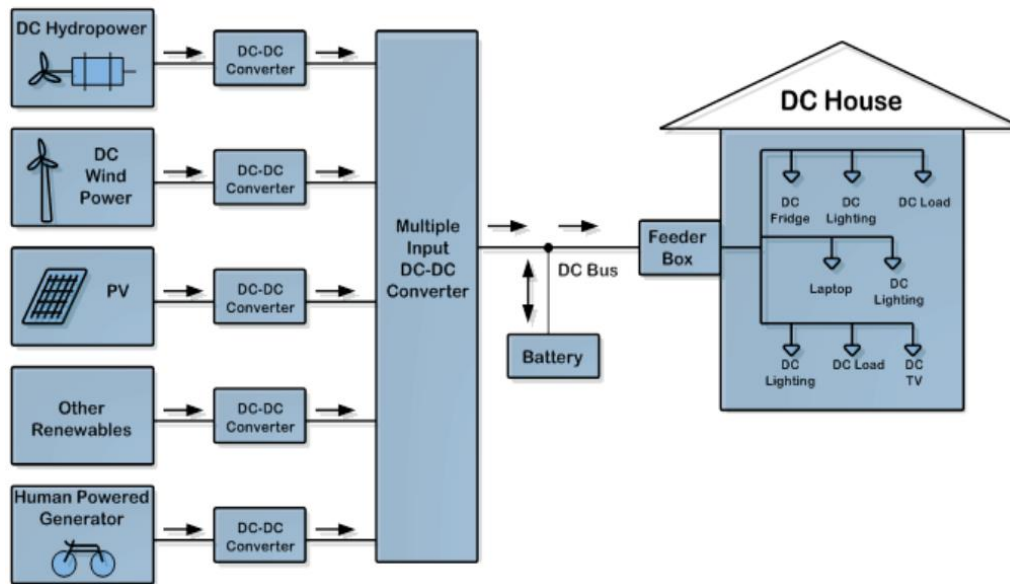


Figure 1-2. Functional block diagram of the DC House project [3]

Several studies have investigated the use of a DC distribution system. In [2], a small-localized DC distribution system for building loads is investigated. This power system is supplied by a DC distributed energy source for the DC loads and has a separate AC grid connection for the AC loads. This methodology leads to a higher efficiency

compared to a system solely based on AC through avoiding the use of the rectifier. In [3], a residential DC electricity has been studied since 2010 at Cal Poly State University to help provide access to electricity in rural, isolated, and remote areas mainly in developing countries by utilizing small-scale renewable energy sources. The DC system is called the DC House where several low power energy sources can be combined into a single DC bus that powers a DC house, as depicted in Figure 1-2. The energy combiner plays an important role in the DC House system and it is made up of stackable DC-DC converters called the Multiple Input Single Output (MISO) converter. Since the inception of the DC House project, several versions of the MISO converter have been developed with various performance and trade-offs as summarized in the next chapter.

2. BACKGROUND

Throughout the world, people are gaining interest in DC electricity once again. The fear that non-renewable fossil-based energy resources are being used up more quickly than they can replace themselves is causing people to turn to renewable energy sources. Additionally, people are looking into DC since converting from AC to DC requires converters which will introduce significant loss [4]. As renewable energy sources are becoming more attractive to power companies and consumers, the use of DC is on the rise again mainly due to the more prevalent use of Photovoltaic (PV) which produces DC electricity [5].

One research effort to utilize DC in everyday life is the DC House project initiated in 2010 at Cal Poly State University [6]. The project aims to promote the use of DC electricity using renewable energy to provide access to electricity in rural areas and areas geographically difficult to be reached by power grid. Rural electrification can be problematic, as distributing power from an AC grid can be expensive due to the need for constructing facilities, transmission lines, and more. Therefore, the most feasible solution for rural electrification is to produce electricity from their general surroundings. The perfect sources for this would be renewable energy resources such as solar, wind, and hydroelectric, which are usually plentiful in these areas [7]. With the exception of PVs and fuel cells which produce DC, when small amount of power needed, the generators used for the renewable energy sources commonly use DC electricity. This consequently calls for the need to use DC to DC converter to convert and control the produced voltage from these renewable resources to the level that people can use.

With the use of DC-DC converters to process the energy produced by renewable energy sources, not only that the voltage matching between source and load can be accomplished, but the DC-DC converters also increase the reliability and efficiency of the overall system [8]. Equally important, the DC to DC conversion process is generally very efficient and not as lossy as the AC to DC conversion. To date there are many types of DC to DC converters, but in general they provide the step-down (buck), step-up (boost), and up/down (buck-boost).

Because energy generation from renewable resources can vary from day to day and even second to second, just as there could be a sudden loss of sunlight with cloud cover coming in, a method to continuously pull in their energy is important. One method to achieve this is by having multiple renewable energy sources to produce the electricity. Within the DC House project, a DC-DC converter that has been developed to accommodate multiple energy sources is called the Multiple Input Single Output (MISO) converter. According to [9], there are four rules to determine whether a converter is allowed to have multiple inputs. The first rule is that all input stages must have a forward conducting bidirectional blocking switch, in which the common output stage must have some control over the power delivered by each source. The next rule is that the connection between the input stage and the common output stage should not have independent controlled switches in parallel. The third rule is that both nodes of input stage capacitor should not both be connected to the common output stage. Lastly, both ends of the input source should not be terminals of the input stage, or else there will be a short circuit if the two input stages with sources with different voltages were connected.

In the end, it was determined that the two most feasible types of converters that can be used as a multiple input converter include the boost and the buck-boost.

Outside of the DC House project, other researchers have proposed and explored MISO converter topologies. One commonly known technical problem with MISO converter is that when the input-stage circuits were put in parallel with a coupled transformer in an interleaving method, the converter was only able to transfer energy from one source to the load at a time. This will in turn produces several performance issues including increased components' stress, uneven thermal distribution, reduced efficiency, and increased cost due to oversizing components in the converter.

One example of MISO converter was proposed by [10]. Figure 2-1 shows the power stage of the converter. As shown, the converter utilizes the current-fed full-bridge converter to address the aforementioned issue; however, it still has complications. It employs a phase shift pulse width modulation technique, in which different power sources are able to transfer into the load. This unfortunately presents switching losses, as there are many power switches used in the topology. Increased complexity also comes in the gating drivers and controller used, which makes the converter expensive and large in size.

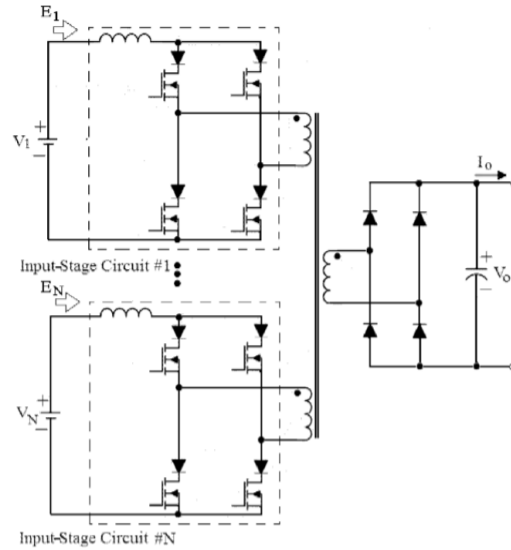


Figure 2-1: Full bridge converter with phase shift pulse width modulation with two inputs [10].

Another previous converter that has been proposed for renewable resources solved these issues [11]. This converter is comprised of two current-fed input stage circuits, a coupled transformer, and a bridge-rectifier, as shown in Figure 2-2. It was a preferred converter at the time as it was simple, consisted of fewer components, a cheaper alternative, and more efficient than the standard converter. However, the issue with this converter for the MISO purpose is that it can only take two inputs, where ideally the MISO converter should be able to take in as many inputs as the user wants.

Another previously explored solution addressed the issue with switching losses. The MISO converter utilizes a soft-switching edge-resonant converter [12-13]. In general, power losses can be present in a multiple input converter, especially in high switching frequency, which will subsequently affect the efficiency. However, with a soft-switching topology, the switching loss can be significantly reduced by achieving zero-

voltage switching and zero-current switching when the switch turns on. In this topology, a maximum of 95.5% efficiency was observed.

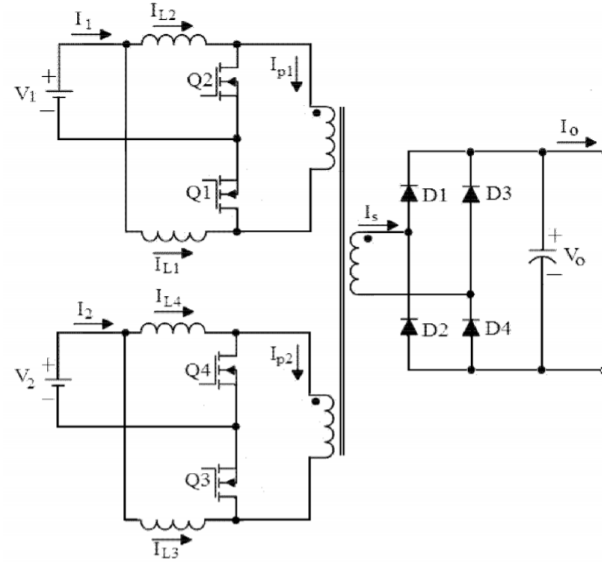


Figure 2-2: Multiple input DC to DC soft-switching edge-resonant converter with two inputs [12-13].

Within the DC House project, there have been multiple students designing different MISO converters. One solution proposed a MISO full-bridge converter [14]. For this converter, the primary side connects all of the sources together and the secondary side combines the energy from the sources to the load. The biggest advantage of the full-bridge converter is that there is only one single primary winding for each source, so there are only three in total, since there are three renewable resources taken into consideration. Consequently, the converter size will be smaller, since there will be a smaller winding area, in addition to a smaller transformer size. Unfortunately, the MISO had somewhat

poor efficiency, never above 80%, and low total output power, around 80W. Another MISO converter was proposed in [15] using the four-switch buck-boost converters and implementing the peak current sharing controller for equal sharing of the sources. The MISO converter was capable of achieving the equal current sharing technique by designating the module with the largest load current as the master, in which all of the other modules will either increase or decrease its own current to match the master's current. Unfortunately, there were still some issues with the proposed converter, namely one MOSFET that appeared to be heating up more than others used in the circuit and relatively poor line regulation of 3%.

Another student proposed and constructed another MISO converter that was flexible, so it would work in different circumstances, not just specific cases [16]. This design utilizes boost converters in order to eliminate the need for transformers, which would introduce losses and decrease efficiency. This high-efficiency MISO converter consists of multiple boost converters in parallel, in order to increase the amount of output power. To prevent any back-feeding voltage, ORing diodes were placed at the outputs to prevent any damage to other outputs. Because this converter incorporates current sharing, the output voltages need to be regulated with great accuracy.

The latest MISO converter development from the DC House project resulted in a US Patent where the converter possesses the desired characteristics of a true MISO converter: scalable in power level, flexible to connect to as many sources, expandable where more MISO modules could be added, equal load sharing, highly efficient, and compact [17].

Despite the success in the MISO converter development, several further improvements are in order. First, protection circuitry such as fusing and inversed polarity must be added. Another improvement is the overall efficiency of the MISO converter at any source and load conditions. Currently, the operation of the MISO converter forces the MISO modules to equally share the load current. This, however, may not be the desired operation since MISO module efficiency is a function of load. For example, at very low load condition, it may be better to operate just one MISO connecting to one source, instead of maintaining the equal load sharing.

To address the aforementioned issue with efficiency improvement of the MISO converter at various loading conditions, this thesis aims to study and investigate the proper mix of current contribution from each MISO module to the total load current requirement to achieve the highest efficiency of the overall MISO converter. The MISO converter will be designed, simulated, and constructed and its performance will be tested and evaluated under unequal load sharing and then compared with those obtained from the equal load sharing case.

3. DESIGN REQUIREMENTS

As stated in the previous chapter, the goal of this design is to maximize efficiency of a MISO converter using unequal current sharing. This project will take in several renewable energy sources and combine them into a single DC bus output. However, to demonstrate the operation and functionality of the proposed method in maximizing the efficiency while keeping the size and cost low, this project will utilize only two sources as shown in Figure 3-1.

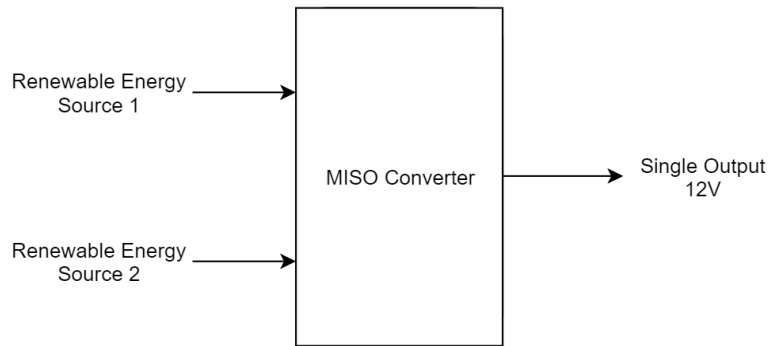


Figure 3-1: Level 0 block diagram.

The input sources will be chosen to come from renewable energy sources, harvested from the sun, wind, water, or human power. From previous DC House projects, in order to generate energy most efficiently, the nominal output voltage of the renewable energy sources is 24V. This input voltage is allowed to vary from 12V to 60V. However, in this thesis the nominal input voltage for the proposed MISO converter will have a tolerance of $\pm 6V$ to simplify the design. Given this, the input voltage will range from 18V to 30V.

In the previous DC House project, the single DC bus output was chosen to be 48 V due to many considerations such as cost, size, efficiency, etc. Therefore, with the 12V to 60V input this would imply that the MISO topology must be a Buck-Boost. In this thesis, the focus is on the method for automatic uneven current sharing to maximize efficiency, and therefore the output voltage is chosen to be 12V to yield the simpler Buck topology for the MISO converter.

Once constructed, the hardware prototype will undergo testing under different loading conditions. This results in the output current of each buck converter to change depending on the efficiency of the MISO. In particular, the MISO's efficiency will be maximized by automatically adjusting the currents from the converters with a microcontroller. Each of the converters will be able to produce different amounts of current to output a total of 3A. Therefore, the intended maximum output power for this project is 36W. Figure 3-2 illustrates the level 1 block diagram of the MISO. A summary of the technical specifications is shown in Table 3-1.

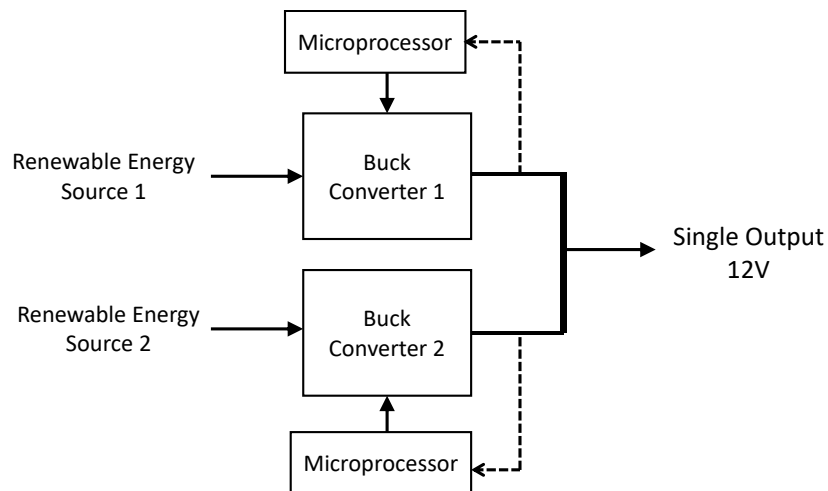


Figure 3-2: Level 1 Block Diagram.

Table 3-1: Summary of Design Requirements

Specification	Value	Justification
Nominal Input Voltage	24V	24V is the nominal output voltage coming from the renewable energy sources.
Input Voltage Tolerance	+/- 6V	This range of input voltage (from 18V to 30V) will account for the renewable energy sources' swings in voltages.
Nominal Output Voltage	12V	As a proof of concept, the nominal output voltage will be 12V to allow the use of a step-down converter.
Output Current	3A	This is selected to keep the size and cost of the overall system low.
Output Power	36W	With an output voltage of 12V and output current of 3A, the total output power will be 36W.

4. DESIGN AND SIMULATION

The premise of this design is to maximize efficiency of the overall system. This MISO converter will have different stages that will have their own purpose to contribute to the overall goal. The first stage will implement diodes and switches to allow the system to use either only one buck converter or to use two converters based on the overall system's efficiency. Figure 4-1 depicts this arrangement. In Chapter 3, it was stated that the output load current would be 3A; however, the output current may need to be larger to allow better test setup and measurements. The next stage, as shown in Figure 4-2, is the paralleled buck converters that will implement uneven current sharing at different loading conditions, from 5A to 7A, since all the components chosen for the two converters are rated for 6A, as the demo boards used for the hardware test are rated at 6.25A each [18].

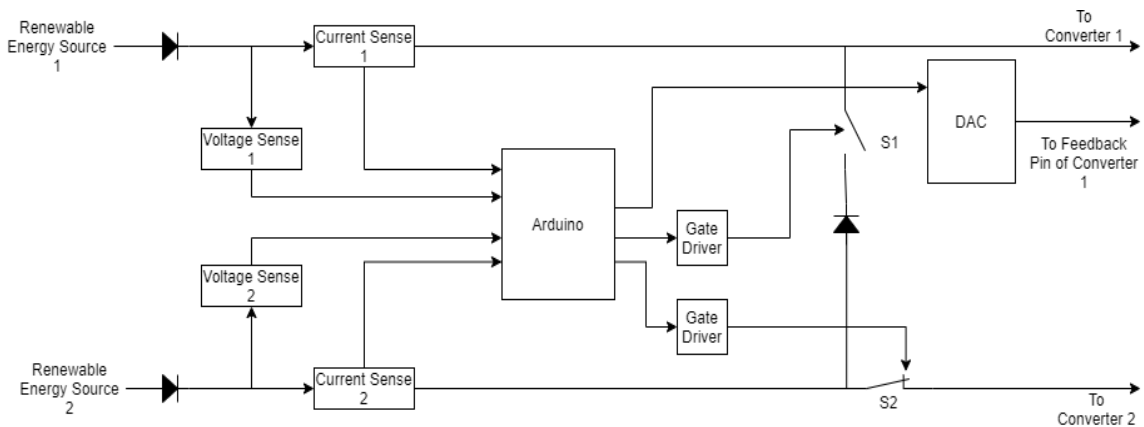


Figure 4-1: Block diagram of stage 1, passthrough stage.

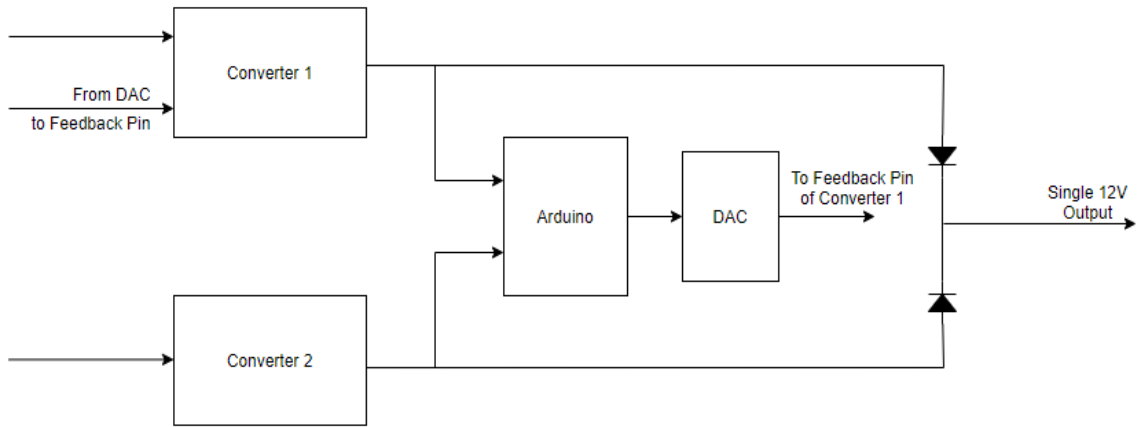


Figure 4-2: Block diagram of stage 2, uneven current sharing.

In the first stage, diodes are placed after the renewable energy sources or power supplies to prevent any backflow of current feeding into any of the power supplies, and switches that are controlled by a gate driver. The MOSFETs that are included in this stage serve as switches to allow one or two converters to be operating at once, which is determined by the efficiencies. There will be current and voltage sensors following the two power supplies, which will be used to determine whether only one or two converters will be connected to the load. The current and voltage sensors provide the needed information for the microcontroller to calculate the input and output powers into the converters, which in turn will determine which converters will be operated. If the sum of the input power is low, then utilizing only one converter may potentially yield a more efficient system. To make this decision, the microcontroller performs the comparison of efficiencies of using one converter versus using two converters, and accordingly will send the appropriate signals for the switches to produce a more efficient system.

The second stage will unevenly split current under different loading conditions. The buck converters will be used to decrease the input voltage down to 12V. This stage will split the current unevenly between the two converters with current ratios of 10/90, 20/80, 30/70, 40/60, and 50/50, which will ultimately combine together again into one single output. The uneven current between the two converters is achieved by injecting a small voltage at the feedback pin of one of the buck converters. This small offset will make the feedback voltage and output voltage of the converter respond accordingly. The more voltage injected at the converter's feedback pin, the more the current from the first converter will decrease. As the small voltage offset at the feedback pin increases, the output voltage decreases slightly, which in turn decreases the current. Then, the second converter, with its feedback pin connected to ground, will output a current that complements the current from the first converter to add up to the load current.

An Arduino will be used for the microcontroller, as it is cheap, readily available, and convenient to use for this application. The Arduino will be incorporated with the switches preceding the converters to help determine whether one or two converters will be connected to the load. The current and voltage sensors are utilized to calculate input power by the Arduino to the converters. The Arduino will then power the gate drivers on and off to close and open the switches. In its default state, the path to using both converters will be closed, so switch S1 will open and switch S2 will be closed, as implied in Figure 4-1, allowing both converters to be used. When testing the efficiency for only one converter, switch S1 will close and switch S2 will open. This causes the power from the second renewable energy source to go through the path of switch S1 and into the first converter along with the power from the first renewable energy source.

The voltage sense will be implemented using a resistor divider due to its simplicity and ideal line regulation characteristic. Essentially, the resistor divider divides the input voltage down by the divider ratio.

$$V_{inArduino} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

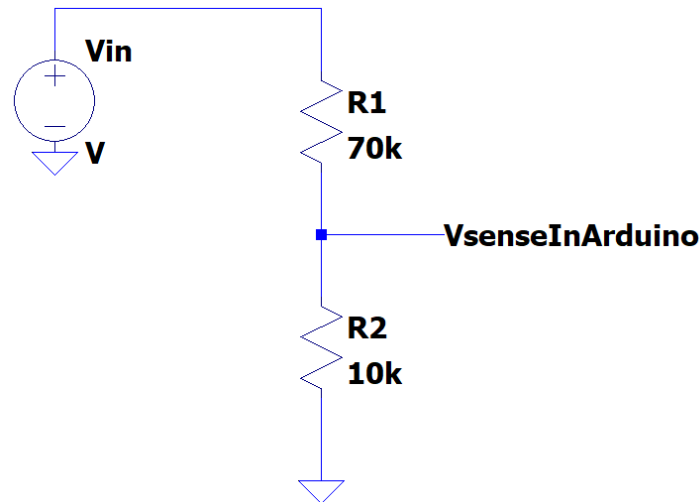


Figure 4-3: Voltage sense by a voltage divider.

Thus, the input voltage will be multiplied by the ratio $\frac{R_2}{R_1+R_2}$. For this project, the chosen ratio is $\frac{1}{8}$, as the input voltage can range from 18V to 30V. This results in the reduced voltage into the Arduino which will range from 2.25V to 3.75V and is lower than the 5V maximum input into analog pins. After the input voltage is divided by a certain ratio, the output voltage of the resistor divider will be read into the Arduino. The Arduino will then read that input analog voltage and multiply it by 8 to get an accurate voltage from the input of the system. The resistor values $75k\Omega$ and $11k\Omega$ were then chosen to be used for the hardware construction since they are nominal 5% resistor values that are

readily available. Therefore, that input analog voltage will be multiplied by $\frac{86}{11}$ in the Arduino.

Next, the INA169 will be used as the current sense amplifier. It works by measuring the differential voltage across a small resistor value, thus converting the current into a voltage. Then, the current will be calculated by the Arduino. In the INA169 datasheet [19], the following equation is used to find external resistors.

$$V_o = \frac{I_s \cdot R_s \cdot R_L}{1k\Omega}$$

The output voltage of the current sense amplifier aims to be 5V since this is the maximum input voltage of the Arduino. A value of 6A was chosen for I_s as this is the maximum current that the components of the converter are rated for. A small and common value of 10m Ω was chosen for the sense resistor. Therefore:

$$5 = \frac{(6A) \cdot (10m\Omega) \cdot R_L}{1k\Omega}$$

$$R_L = 83.33k\Omega$$

With these measured voltages and currents, the Arduino can now calculate an accurate input power. The final value used for the resistor was 82k Ω since it is a commercially available nominal resistor value closest to the calculated resistor value. Furthermore, the smaller resistor value also ensures that the 5V maximum limit of the Arduino will not be exceeded. Then, I_s can be found by rearranging the previous equation.

$$I_s = \frac{V_o \cdot 1k\Omega}{R_s \cdot R_L},$$

where $R_L = 83.33k\Omega$, $R_s = 10m\Omega$, and V_o is the analog input voltage to the Arduino.

Therefore,

$$I_s = V_o \cdot \frac{50}{41}$$

After reading the analog input voltage into the Arduino, the current will be calculated by multiplying the analog input voltage by the ratio $\frac{50}{41}$.

Another component is the gate driver. This is the component that will be used to enable the MOSFETs to pass or block the voltages. The gate driver that will be used is the LTC7001 [20]. It was chosen due to its high input voltage input capability, up to 135V. Even though the gate driver's input voltage may be higher than necessary, the wide input voltage is useful to protect from for any transient swings or spikes from input voltage without using additional protection device. The Arduino will provide 0V to 5V pulses to the gate driver's INP pin that will turn on and off the MOSFET. The gate driver uses a bootstrap diode and capacitor to charge up to a voltage greater than the 24V input connected to the gate of the MOSFET, which allows the MOSFET to turn on. This process is applied to both S1 and S2.

The high voltage N-channel MOSFET [21] used as the switch to block or pass the power from the renewable energy sources to the converters has a few main factors to consider when sizing it. This includes the maximum voltage and average current. Based on the circuit, the MOSFET should be able to handle a maximum voltage of 30V to account for the extra +6V swing and a maximum current of 2.227A if the input is 18V.

MOSFET AO4484 from Alpha and Omega Semiconductor matched all the specifications and was therefore chosen for this project. The MOSFET has its maximum voltage at 40V, the maximum drain current rating of 10A, and steady-state maximum junction-to-ambient of 75°C/W.

Additionally, the Arduino will be programmed by the user to inject voltage at the feedback pin of the first converter. Because 0.1mV resolution is desired, a high precision digital to analog converter (DAC) must be used. The Arduino will be used to power the DAC. The DAC8801 from Texas Instruments [22] has a serial peripheral interface (SPI) protocol that will be used in this operation. It is also a 14-bit DAC, which will provide enough resolution for the injected voltage as calculated below. The reference voltage V_{ref} chosen was 1.8V so that the voltage step would be small enough for the resolution that is desired, which is in the 0.1mV range.

$$V_{step} = \frac{V_{ref}}{2^{14}}, \text{ where } V_{ref} = 1.8V$$

$$V_{step} = \frac{1.8V}{16384} = 0.11 \text{ mV}$$

Because the desired resolution is so small, the DAC chosen needed to have extremely little noise, as any noise can disrupt the operation of the system. The DAC's differential nonlinearity (DNL), which is the variation between two analog values corresponding to its respective digital values, must be considered. The DAC8801's maximum DNL value is ± 0.5 , which means for one digital value, its corresponding analog value can swing $\pm 0.055mV$ of its corresponding analog value.

$$\text{Analog value swing} = 1 \text{ LSB} \cdot \text{DNL} = 0.11mV \cdot 0.5 = \pm 0.055mV$$

Therefore, the injected voltage with a swing of $\pm 0.055mV$ will correspond to one digital value. This resolution from this DAC meets the desired resolution.

Moreover, since the DAC's reference voltage V_{ref} is 1.8V, a Zener diode is used to bring 5V down to 1.8V. From the datasheet, the DAC's reference pin has an input resistance of $5k\Omega$. Therefore, as shown in the following equation, it requires about $360\mu A$.

$$I_{ref} = \frac{V_{ref}}{R_{ref}} = \frac{1.8V}{5k\Omega} = 360\mu A$$

To allow extra current in case of any spikes on the reference pin, the reference pin current was increased to $410\mu A$.

For the Zener diode, the MMSZ4678T1G was selected whose reverse voltage is 1.8V. In the datasheet [23], the reverse current of this specific diode is $50\mu A$. A value of $6.8k\Omega$ was chosen for the resistor since it is a 5% standard value. Therefore, $60\mu A$ will be the expected reverse current through the Zener diode, which is similar to the datasheet's specified reverse current with a $10\mu A$ leeway. The value of the resistance is calculated in the following equation.

$$R = \frac{V_R}{I_R} = \frac{V_{DD} - V_{ref}}{410\mu A + 60\mu A} = \frac{5V - 1.8V}{470\mu A} = 6.8k\Omega.$$

A capacitor value of $0.1\mu F$ was chosen since it is a standard value that is easily accessible. The capacitor in parallel with the resistor and Zener diode is used to stabilize the voltage and thereby smoothing the output voltage.

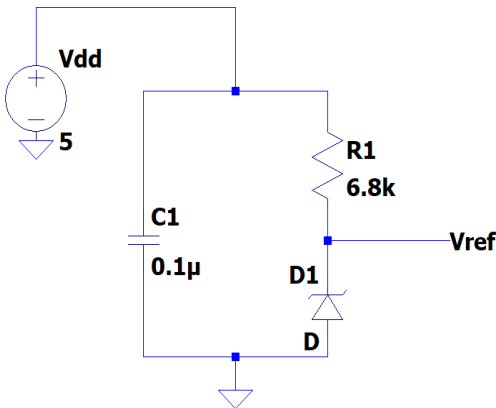


Figure 4-4: Zener diode as a voltage reference for the DAC.

The step-down converter, the LT3845 [24] was chosen. It is a high voltage synchronous buck converter which operates at a typical value of 300kHz and up to 60V. The voltage rating is higher than needed, but is useful to account for any spikes from the renewable energy sources without using any extra protection device. The converters are to step down from a nominal 24V with a swing of $\pm 6V$ to 12V. This yields a duty cycle of approximately 50%. The converter component values were sized according to the desired values. When sizing an inductor for the converter, the biggest consideration is the inductor current because of the loss it can impact with the DC resistance (DCR) of the inductor. Therefore, choosing an inductor with small DC resistance is crucial. Also, as current through the inductor increases, the inductor eventually begins to saturate and behaves like a resistor and the value of the inductor decreases. Therefore, it is necessary to choose a higher value inductor to compensate for the loss of inductance. The critical inductance was calculated using the equation that is derived below.

$$Duty\ Cycle, D = \frac{V_o}{V_{in}} = \frac{12V}{24V} = 0.5$$

$$V_L = L \frac{di_L}{dt} \Rightarrow |-\bar{V}_o| = L \frac{\Delta i_L}{\Delta t} \text{ for inductor OFF time}$$

$$\Rightarrow L_c = \frac{\Delta t_{off} \cdot \bar{V}_o}{\Delta i_L} = \frac{\bar{V}_o \cdot (1 - D)}{\Delta i_L \cdot f}$$

$$L_c = \frac{\bar{V}_o \cdot (1 - D)}{\Delta i_L \cdot f} = \frac{\bar{V}_o \cdot (1 - D)}{(0.35 \cdot I_{max}) \cdot f} = \frac{12 \cdot (1 - 0.5)}{(0.35 \cdot 6) \cdot 300k} = 9.52 \mu H$$

As shown in the above calculation, the peak to peak current ripple Δi_L is chosen to be 35% of the maximum output current. This is to follow the common practice of choosing Δi_L to be in between 30% to 40%. In order to compensate for the loss of inductance, a higher inductor value, $15 \mu H$, was chosen. As seen in Figure 4-5, for the inductor MPX1D1264L220 inductor [25] whose nominal value is $22 \mu H$, its inductance decreases down to around $17 \mu H$ at 6A.

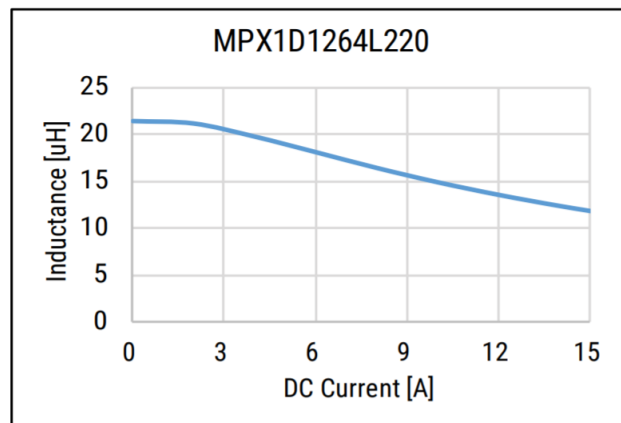


Figure 4-5: MPX1D1264L220's inductance value vs. current graph.

Next, the following equations that are followed by their derivations were used to size the critical output capacitance.

$$q = C_o \cdot \Delta V_o \Rightarrow +q \text{ area of the } i_{c,output}(t) \text{ waveform} = C_o \cdot \Delta V_o$$

$$\Rightarrow \frac{1}{2} \cdot \frac{\Delta i_L}{2} \cdot \frac{T}{2} = C_o \cdot \Delta V_o \Rightarrow \frac{\Delta i_L}{8 \cdot f} = C_o \cdot \Delta V_o$$

Thus,

$$C_o = \frac{\Delta i_L}{\Delta V_o \cdot 8f} = \left[\frac{\bar{V}_o \cdot (1-D) \cdot T}{L} \right] \frac{1}{\Delta V_o \cdot 8f} = \frac{\bar{V}_o \cdot (1-D)}{\Delta V_o \cdot 8L \cdot f^2} = \frac{(1-D)}{\frac{\Delta V_o}{\bar{V}_o} \cdot 8L \cdot f^2}$$

$$C_o = \frac{(1-D)}{\frac{\Delta V_o}{\bar{V}_o} \cdot 8L \cdot f^2}, \text{ where } \frac{\Delta V_o}{\bar{V}_o} \text{ is chosen as 2\%, or 0.02}$$

$$C_o = \frac{1 - 0.5}{0.02 \cdot 8 \cdot L \cdot f^2} = \frac{0.5}{1.6 \cdot 9.52\mu \cdot 300k^2} = 3.65\mu F$$

Then, for the critical input capacitance equation is derived below.

$$q = C_{in} \cdot \Delta V_{in} \Rightarrow -q \text{ area of the } i_{c,input}(t) \text{ waveform} = C_{in} \cdot \Delta V_{in}$$

$$C_{in} = \frac{\bar{I}_{swmax} \cdot (1-D)T}{\Delta V_{in}} = \frac{D \cdot \bar{I}_{omax} \cdot (1-D)T}{\Delta V_{in}} = \frac{D(1-D)\bar{V}_o}{\Delta V_{in} \cdot f \cdot R_{min}}$$

Thus,

$$C_{in} = \frac{D(1-D)\bar{V}_o}{\Delta V_{in} \cdot f \cdot R_{min}},$$

$$\text{where } R_{min} = \frac{V_o}{I_{max}} = \frac{12V}{6A} = 2\Omega \text{ and } \Delta V_{in} = 2\% \text{ of } 24V = 24V \cdot 0.02$$

$$C_{in} = \frac{0.5 \cdot (1 - 0.5) \cdot 12}{(0.02 \cdot 24) \cdot 300k \cdot 2} = 10.42\mu F$$

In practice, 2% peak to peak voltages in relation to its average voltage is typically used as the maximum voltage ripple requirement. A larger output capacitance value was chosen to smooth the output voltage even more at the expense of a slower transient response and cost. However, the transient time in this project is not considered as important as the accuracy of the output voltage. Therefore, a large value of $100\mu F$ was chosen to minimize the output ripples. By the same token, a larger $80\mu F$ for C_{in} was also chosen. Additionally, when sizing the output capacitor, another important consideration is the capacitor's equivalent series resistance (ESR). As stated previously, the output capacitors help minimize the ripples of the output voltage and so one technique to reduce ESR is by placing output capacitors in parallel. Furthermore, as voltage is applied across a capacitor, the value of the capacitance decreases. Following these considerations, four capacitors were used: two $68\mu F$, one $22\mu F$, and one $1\mu F$ capacitor. After the decrease of the capacitance value of the four capacitors, the total capacitance amounts to around $100\mu F$. Similarly, the multiple input capacitors were used to help decrease ESR and ripple, resulting in the use of one $47\mu F$ and two $2.2\mu F$.

The R_{sense} is another important component of the buck converter since it is used to monitor the current through the inductor. The value was calculated from the following equation in the LT3845 datasheet, where $I_{out,max}$ is around 6A.

$$R_{sense} = \frac{70mV}{I_{out,max}} = \frac{70mV}{6A} = 11.667m\Omega$$

Therefore, a sense resistor value of $10m\Omega$ was chosen since it is the closest nominal value available on the market.

As for the MOSFET in the buck converter, there are many factors to consider when choosing MOSFET. As stated previously, the main factors to consider when sizing a MOSFET include the maximum voltage, average current, power, and junction temperature. The same MOSFET as the ones used for the first stage of the design, AO4484, can also be used for the buck converter since it meets all of the design specifications. In the simulations, the results of the MOSFET at boundary conditions is as follows: the maximum voltage spike is 24.6V, the average current is 6A, and the average power is 195mW bringing the MOSFET to a maximum of 40°C.

Lastly, the feedback resistors were changed in hopes of making the resolution of the injected voltage better. Even though decreasing the feedback resistors did not change the resolution of the injected voltage, the new resistor values were kept, as they are standard resistor values, readily available, and this resistor divider combination makes a desired higher output voltage of the buck converter than the intended 12V. The output voltage was intended to be higher than 12V to account for the diode drops after the buck converters. The resistor R_1 of Figure 4-6 was first chosen to be 9.53k Ω as it is a nominal 1% standard resistor. Then, R_2 of Figure 4-6 was then calculated by the following equation found in the LT3845 datasheet.

$$R_2 = R_1 \cdot \left(\frac{V_{out}}{1.231V} - 1 \right), \text{ where } V_{out} = 12.7V \text{ and } R_1 = 9.53k\Omega$$

$$R_2 = 9.53k \cdot \left(\frac{12.7}{1.231V} - 1 \right) = 88.8k\Omega$$

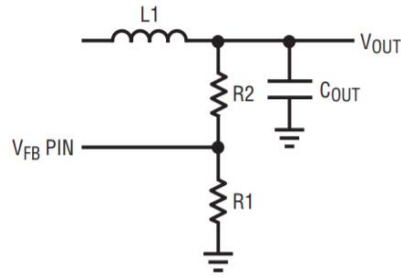


Figure 4-6: Resistor divider on external pin of V_{FB} .

A nominal 5% resistor of $91k\Omega$ was then chosen, as it is a readily available resistor. The value of R_1 and R_2 from the datasheet corresponds to R_6 , R_{13} and R_5 , R_{12} of the simulations in Figure 4-7, respectively.

Next, the design is simulated in LTSpice. However, since the first stage deals with making the decision of using one or two converters, therefore only the second stage consisting the actual converters is simulated. The goal of the simulations in LTSpice of the MISO converter is to be able to unevenly split current between the two converters, which will eventually combine to the value of the load current while maintaining an output voltage of 12V. The load current will vary from 5A to 7A, with the current rating of the individual converters to be rated at 6.25A. Following the first stage of determining which converter should be connected to the output, the converters are first set in parallel, as seen in Figure 4-7, and assigned uneven current sharing.

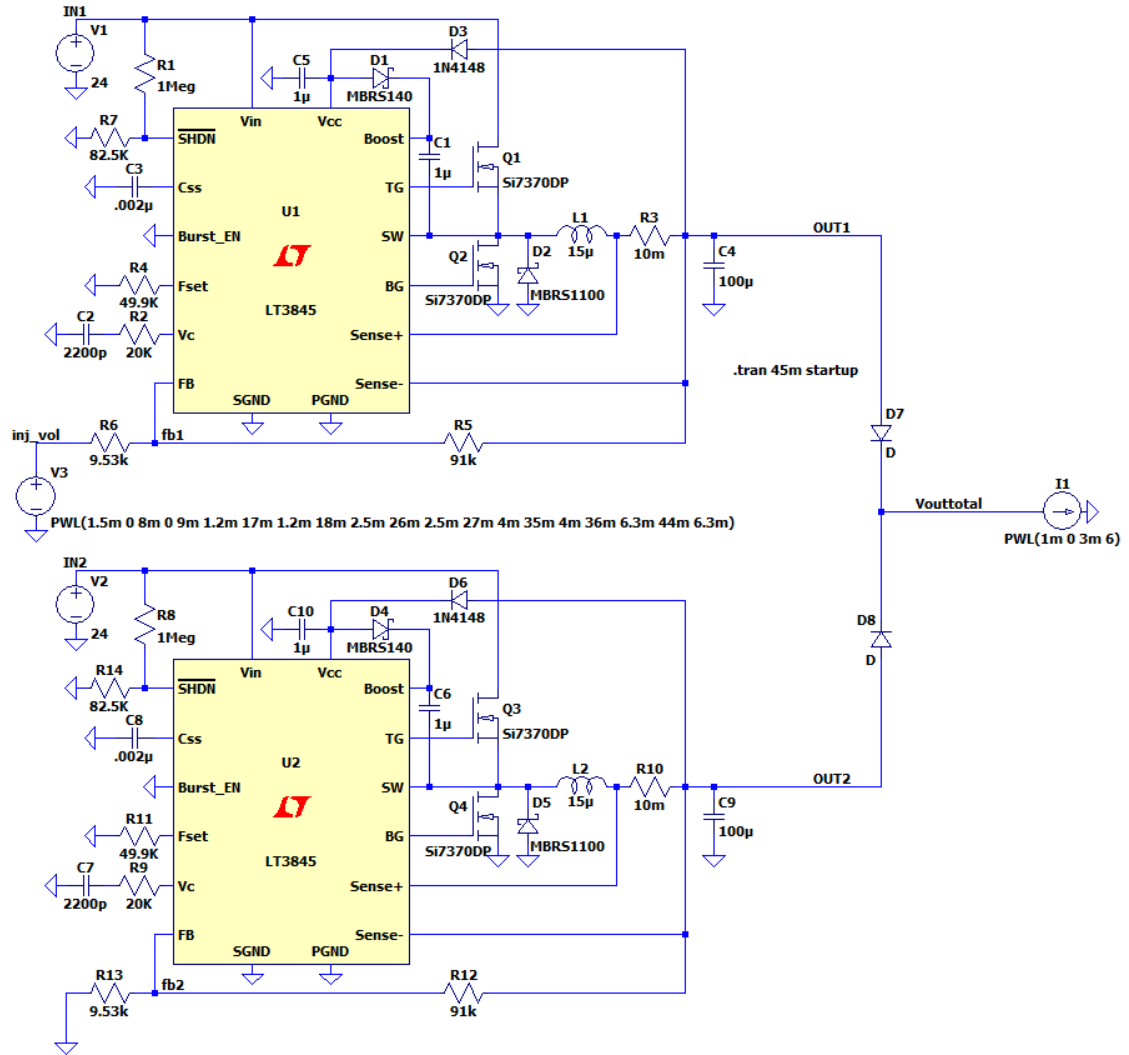


Figure 4-7: Circuit with two paralleled buck converters used to unevenly split current.

The loading current will differ depending on what application is needed and, in this project, will be varied from 5A to 7A. The injected voltage is applied to the feedback pin of only the first converter, while the second converter's feedback pin is connected to ground. Injecting voltage to only one converter allows for more convenient testing, as there are less variables to monitor while testing. The feedback pin of a step-down converter helps to determine whether the output is at 12V. According to the LT3845

datasheet, the converter desires an external voltage of 1.231V at the feedback pin for an output of 12V. This external voltage is internally connected into an error amplifier. If the voltage is not at 1.231V, the buck converter will act accordingly and adjust the output voltage until it returns back to 12V output. In this simulation, a small positive voltage is applied to the feedback pin, in which the output voltage decreases slightly. Doing so will trick the converter into believing that the output voltage had reached the desired 12V. Therefore, as the injected voltage at the feedback pin increases, the output voltage will decrease slightly, thereby the output current of the converter must act appropriately by decreasing its value. Because the second converter does not have a voltage injected at the feedback pin, it will behave like a regular buck converter; however, it will output a current that ensures that the sum of the two currents from the converters add up to the demanded output load current. In this simulation, output voltages of 12.7V from each individual converters are desired since two diodes are placed following the converters to prevent any backflow of current into the buck. After the diode drop of around 0.7V, the total output voltage of the whole system should be at the desired 12V.



Figure 4-8: Simulation of current splitting with 6A load current.

Figure 4-8 illustrates the simulation of the paralleled buck converters with a 6A load. The total output voltage waveform illustrates that it is always around 12V. Near the beginning of the simulation, at around 1.5ms, the current starts to split into a 50/50 ratio. At this time, there is a slight drop, 0.7V, on the total voltage output due to the voltage drop across the diodes. We can also observe from Figure 4-8 that the output voltage actually decreases very little as the injected voltage increases. As the output voltage starts to steady out at its own particular voltage per injected voltage value, the feedback voltage starts leveling out at the desired 1.231V. This tells the buck converter that the output

voltage is at the right level and to stop increasing or decreasing the output voltage. In the simulations, as the injected voltage starts to increase, the output voltage decreases very slightly, in which the output current also decreases.

The model used in this simulation is close to an ideal model. This means there are no stray and parasitic components incorporated in the model. This results in the same efficiency curves of the two converters. Figure 4-9 illustrates the efficiency curves of the identical converters with load currents 6A, 7A, and 8A.

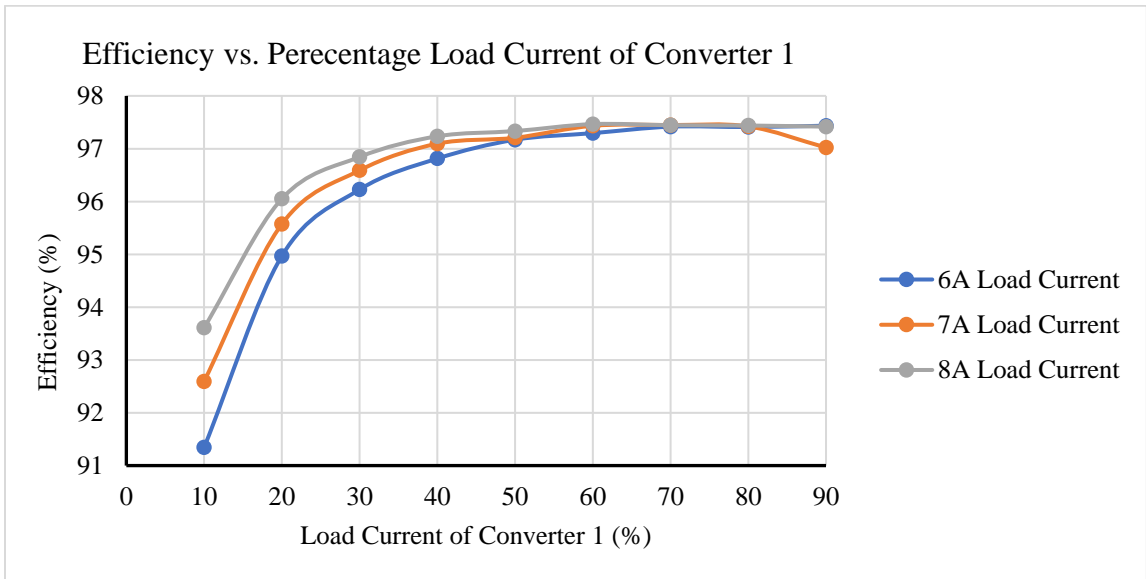


Figure 4-9: Efficiency vs. percentage load current percentage with identical converters.

In practice, the converters will not be identical to each other. For example, the DC resistance (DCR) of the inductor in one converter or the actual switching frequency of one converter may be slightly different from the other. With these minor differences, the efficiency curves of the individual converters will be different. The uneven splitting of

current between the two individual converters will then be recorded by the Arduino. Then, the Arduino will be able to determine which current ratio, and the injected voltage, to produce in order to achieve the greatest efficiency.

With DCR of 0.0833Ω on one converter, no DCR on the other converter, and a total output load current of 6A, the efficiency curves are shown in Figure 4-10. The DCR of 0.0833Ω was chosen to force 3W loss at the output. Because $P = I^2 \cdot R$, and $P = 3W$ and $I = 6A$, $R = 0.0833\Omega$. This illustrates that with minor parasitic losses, the efficiency may decrease dramatically. As depicted in Figure 4-10, at all load current percentages the converter with no DCR will always be more efficient than its counterpart.

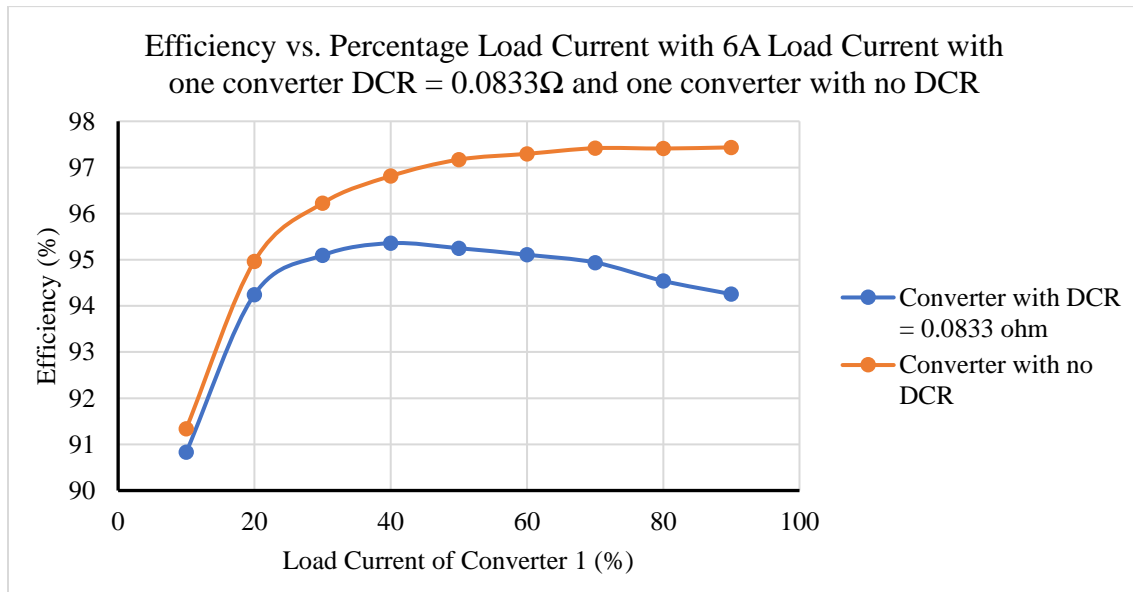


Figure 4-10: Efficiency vs. percentage of 6A load current; one converter with DCR = 0.08Ω and one converter with no DCR.

Another case that was tested is if both converters have DCR, one much larger than the other. A DCR value of 0.0833Ω was chosen to force a 3W loss at the output, and

a DCR value of 0.5Ω was chosen to force a 18W loss at the output. These two extreme DCR values are used in order to demonstrate that the differences in the two converters will illustrate different efficiency graphs. Figure 4-11 illustrates that DCR decreases the efficiency of the converter. With these efficiency graphs, it is clearly more efficient to run at 20% load current when DCR is 0.5Ω and 80% load current when DCR is 0.08Ω rather than the combination of 80% load current when DCR is 0.5Ω and 20% load current when DCR is 0.08Ω .

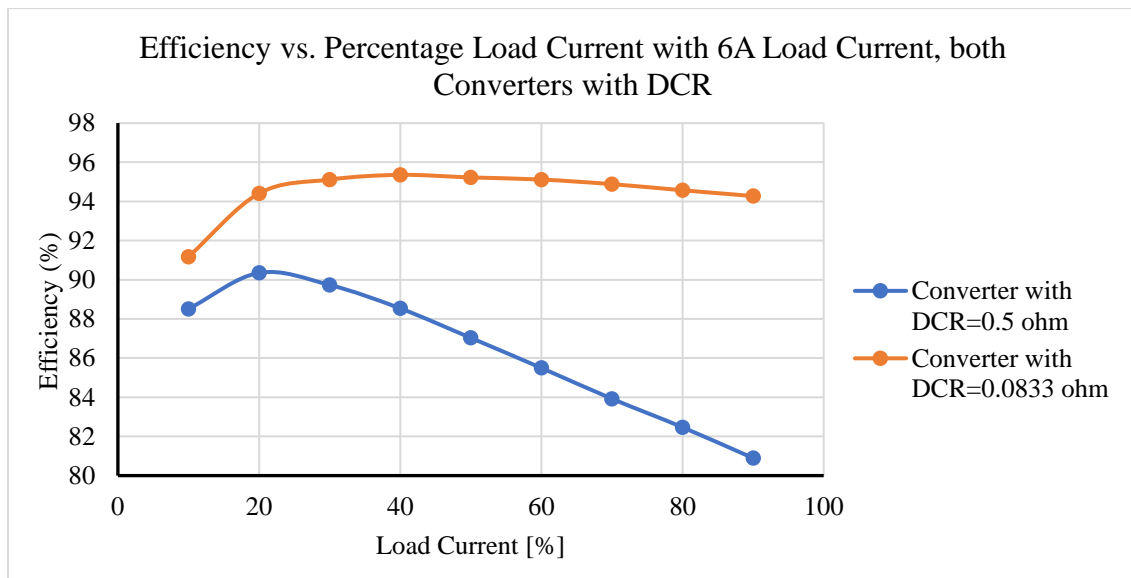


Figure 4-11: Efficiency vs percentage of 6A load current; one converter with DCR = 0.08Ω and one converter with DCR = 0.5Ω .

Another practical scenario that may produce differences in efficiency curves is if the switching frequencies of the two converters are not matched. Currently, the typical switching frequency of the LT3845 converters are 300kHz. The LT3845 datasheet

illustrates how to change the switching frequency by calculating for the external resistor at the F_{set} pin:

$$R_{set} = 8.4 \cdot 10^4 \cdot f_{sw}^{(-1.31)},$$

where R_{set} is in $k\Omega$ and f_{sw} is in kHz

For a switching frequency of 300kHz, the R_{set} value of both converters should be 47.78k Ω . Therefore, the closest standard resistor value is 47k Ω . However, it is very likely that the resistor values between the two converters will differ by a tiny amount. For a resistor tolerance of $\pm 5\%$, the worst-case scenario will be when one converter's R_{set} value is -5%, 44.65k Ω , and when the other converter's R_{set} value is +5%, 49.35k Ω . Therefore, with these two different R_{set} values, the corresponding frequencies are 315.93kHz and 292.69kHz, respectively, which have been calculated from the aforementioned equation. No DCR is added to this simulation to have less variables while testing. Figure 4-12 illustrates the two different efficiency curves when the switching frequencies differ slightly.

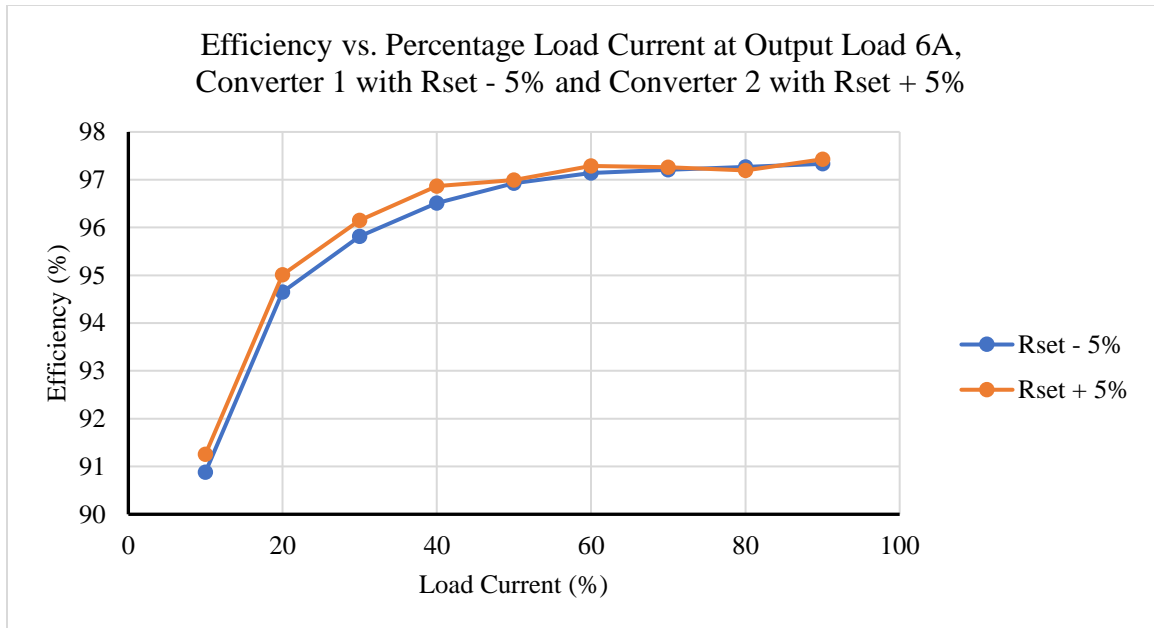


Figure 4-12: Efficiency vs. percentage of 6A load current; one converter with R-5% and one converter with R+5%.

As illustrated in Figure 4-12, the switching frequency does not affect the efficiency too much, and the slight differences in resistances, thus frequencies, are negligible.

As illustrated from the simulations, different parasitics may introduce a change in efficiency. Initially, when the converters are perfectly the same in simulation, there is hardly any difference with varying loads. However, once parasitics are introduced, the efficiency graphs change to match the amount of losses from the buck converter; the more parasitics the efficiency will most likely decrease. The differences in efficiencies between the two converters illustrate that the specific choosing of different ratios can result in the maximum efficiency of the circuit. Ultimately, simulation proved that the

splitting of currents was successful when applying a small voltage in place of the ground node at the feedback pin of the buck converter.

5. HARDWARE DESIGN AND RESULTS

In this chapter, the hardware design, construction, and results are discussed.

The stage 1, shown in Figure 5-1, is used as a passthrough stage. The Arduino will be utilized to apply 0V or 5V to the input of the gate driver to turn on or off switches S1 and S2. More specifically the 0V from the Arduino will open the switch while the 5V signal will close the switch.

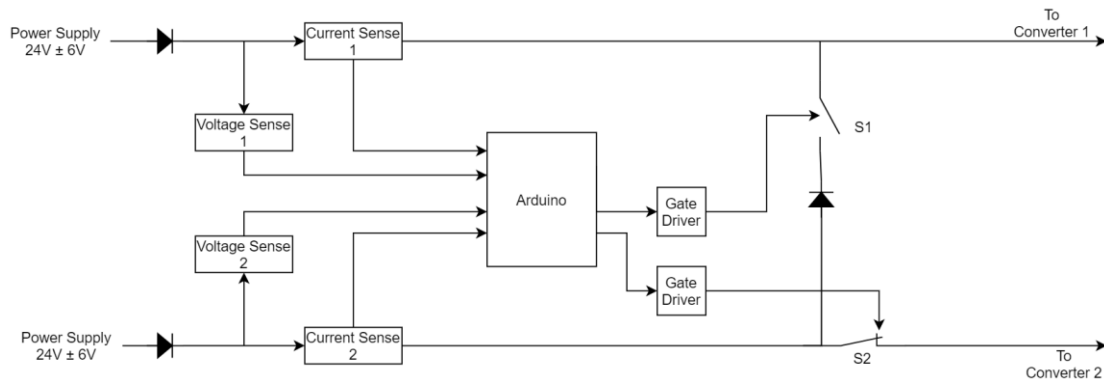


Figure 5-1: Block diagram of stage 1, passthrough stage.

Stage 1 is solely used to allow the circuit to use either converter 1 or both converters at once. Because there is a diode between the power paths, current will only be able to flow from the bottom power path to the top power path, which means that only converter 1, and not just converter 2, can be used by itself. All but one ratio case will have S1 open and S2 closed. Only one case will close S1 and open S2, which is the 100% / 0% ratio case where only converter 1 will be used.

For testing stage 1, there were two loads used on the two outputs of the board. Figure 5-2 illustrates the test setup and the highlighted paths that were used for the test.

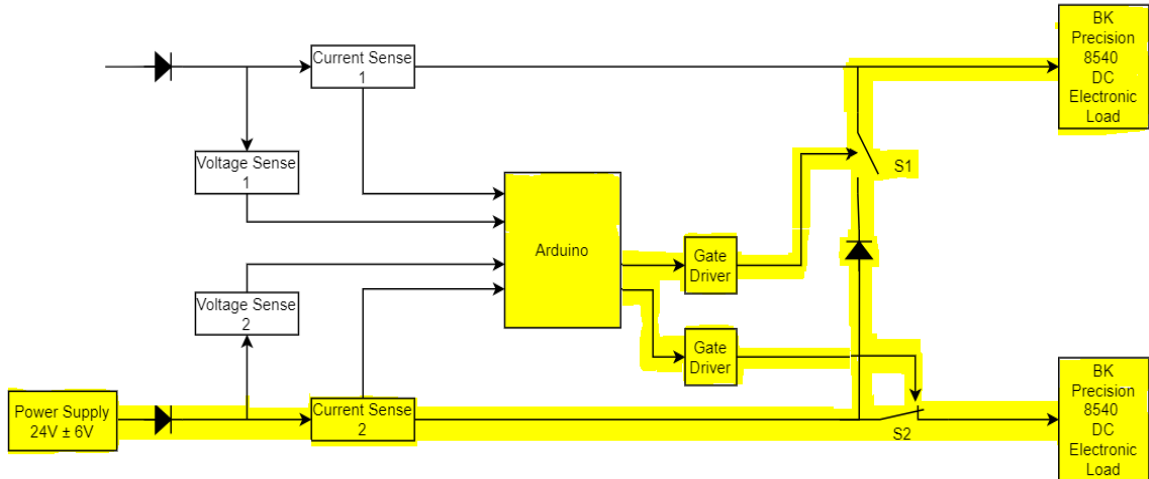


Figure 5-2: Test setup of stage 1.

There were two parts done during this test. The DC electronic loads were set to 1A per output. The first test was to turn off (open) switch S1 and to turn on (close) switch S2. This configuration occurs when the current will split unevenly between the two converters for all the different ratios except for 100% / 0%. The Arduino was programmed to turn off switch S1 by providing 0V to the input pin of the first gate driver, and to turn on switch S2 by providing 5V to the input pin of the second gate driver. Figure 5-4 illustrates that the top DC electronic load, which belongs to the path of switch S1, pulls in 0A, and that the bottom DC electronic load, which belongs to the path of switch S2, has 1A running through it. Additionally, the power supply is supplying 1A, suggesting that only one path with 1A is running through it.

```

#include <SPI.h>

const int Input1 = 11; // input 1
const int Input2 = 12; // input 2

void setup() {
  Serial.begin(9600);

  pinMode(Input1, OUTPUT);
  pinMode(Input2, OUTPUT);
  digitalWrite(Input1, LOW); //off
  digitalWrite(Input2, HIGH); //on
  SPI.begin();
}

```

Figure 5-3: Part of Arduino code illustrating switch S1 off and switch S2 on.

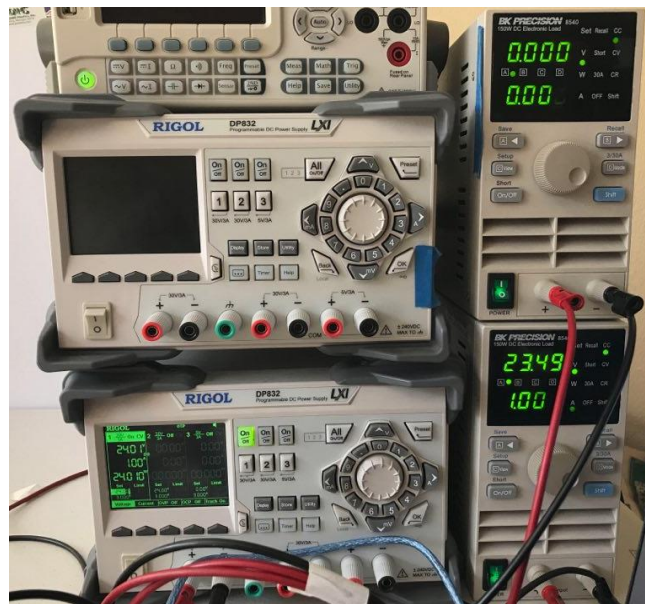


Figure 5-4: Test results for switch S1 off and switch S2 on.

The next test was to test the opposite, where switch S1 is closed (turned on), and switch S2 is open (turned off). This configuration is to test the 100% / 0% load current ratio, where only converter 1 will be used. The Arduino was programmed to turn on

switch S1 by providing 5V to the input pin of the first gate driver, and to turn off switch S2 by providing 0V to the input pin of the second gate driver. Figure 5-6 illustrates that the top DC electronic load, which belongs to the path of switch S1, pulls in 1A, and that the bottom DC electronic load, which belongs to the path of switch S2, has no current running through it. Additionally, the power supply is supplying 1A, suggesting that only one path with 1A is running through it. Figure 5-7 illustrates the physical protoboard for stage 1, the passthrough stage.

```
#include <SPI.h>

const int Input1 = 11; // input 1
const int Input2 = 12; // input 2

void setup() {
  Serial.begin(9600);

  pinMode(Input1, OUTPUT);
  pinMode(Input2, OUTPUT);
  digitalWrite(Input1, HIGH); //on
  digitalWrite(Input2, LOW); //off
  SPI.begin();
}
```

Figure 5-5: Arduino code illustrating switch S1 on and switch S2 off.

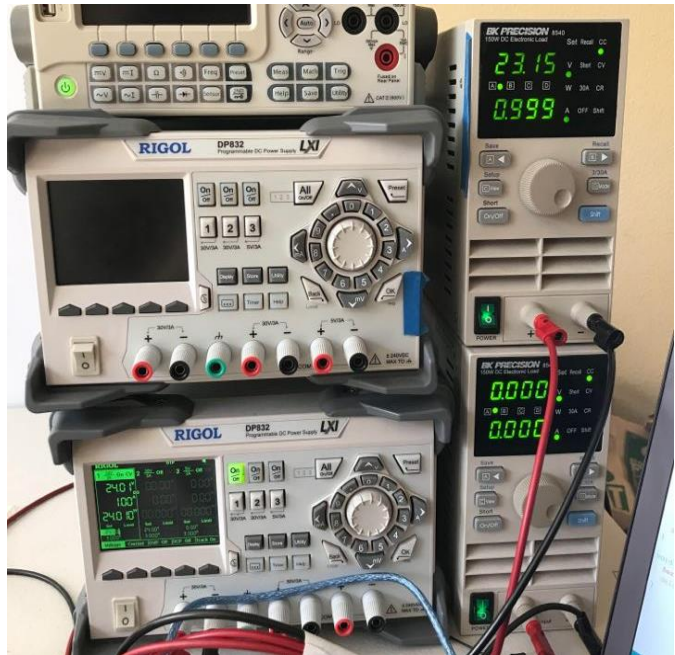


Figure 5-6: Test results for switch S1 on and switch S2 off.

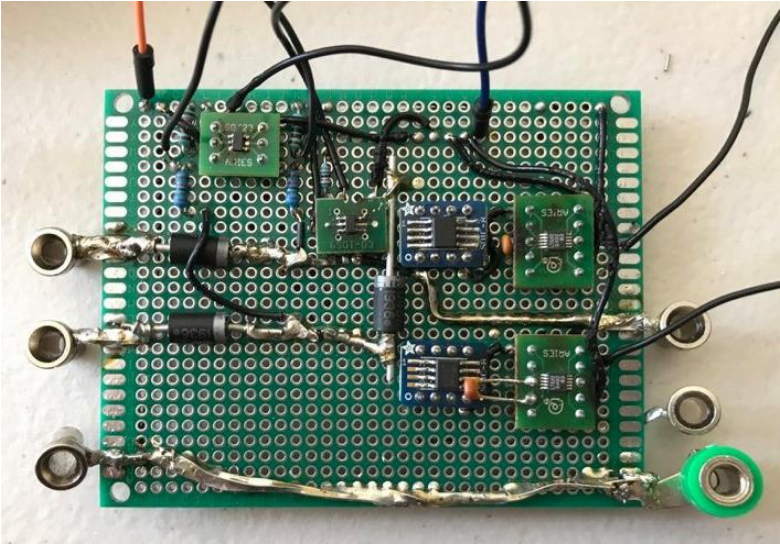


Figure 5-7: Stage 1 protoboard.

The block diagram of Stage 2, which combines the outputs of the converters into one single 12V bus, has been modified from Chapter 4 to illustrate the injected voltages to both converters as seen in Figure 5-8.

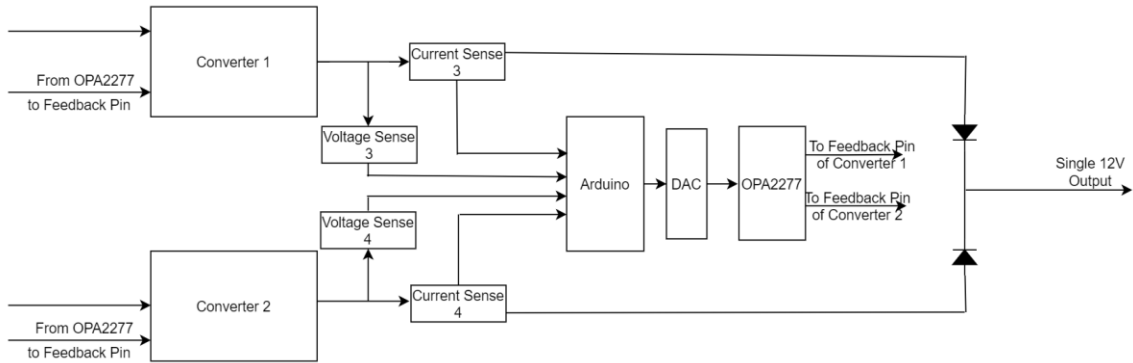


Figure 5-8: Block diagram of stage 2, uneven current sharing.

In the previous chapter, the applied voltage at the FB node was supposed to be done only to the top converter. However, as the hardware testing progressed, it was determined that it would be more convenient to apply voltages at both FB nodes to help create the different ratios.

As stated in the previous chapter, this stage’s goal is to unevenly split the load current between the two converters. The uneven splitting of the load current is done by applying a small voltage at the feedback pins of the converters. On both of the LT3845 demo boards, the 0402-sized R8 and R9, as seen highlighted in Figure 5-9, and its demo board in Figure 5-10, were replaced with 9.53k Ω and 91k Ω resistors. Both figures were found in the “DC1073 - LT3845EFE Evaluation Kit Quick Start Guide” manual. The

grounded part of R8 was then lifted from the ground trace and connected by a wire to the DAC's current to voltage amplifier OPA2277, which are both on the protoboard.

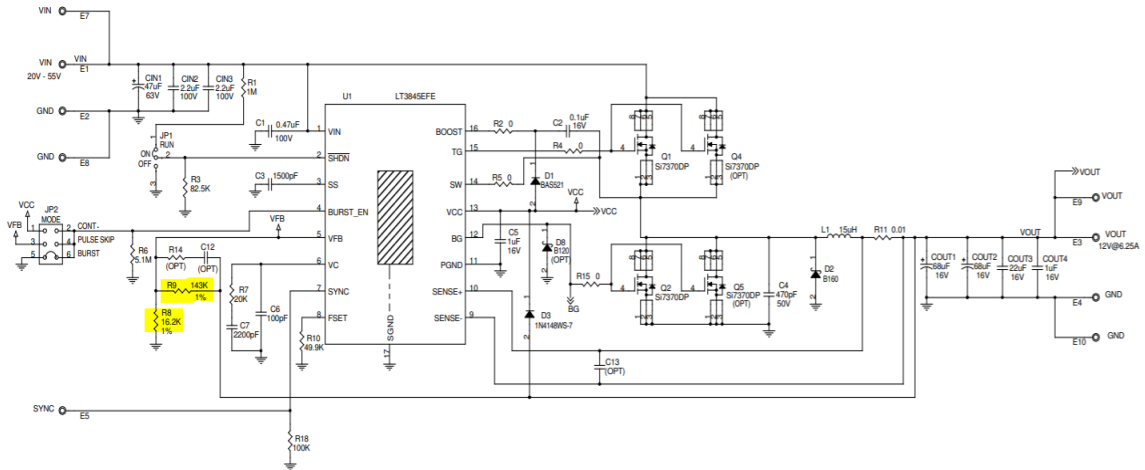


Figure 5-9: Schematic of LT3845 demo board, R8 and R9 highlighted.

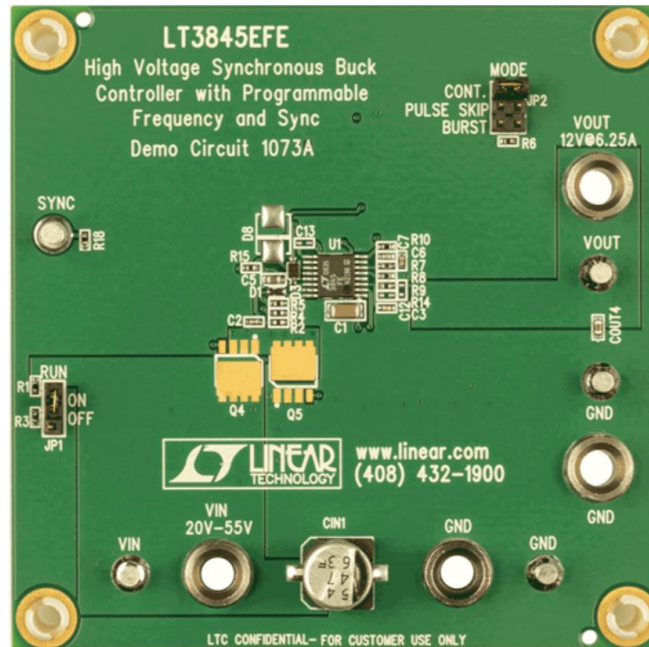


Figure 5-10: LT3845 demo board.

Prior to modifying the demo board, Linear Technology stated that it could take a V_{in} that would range from 20V to 55V and would be able to output 12V at 6.25A. During testing, the demo board could only operate up to 5A, most likely due to the different FB resistor values that allows for higher output voltage. The reason for a desired higher output voltage is to account for the diode drop following the converters. Because the RIGOL DP832 DC Power Supply has a maximum power output of 90W, the higher the load current means that the power supply will need to deliver more current. Once the power supply outputs 90W, its voltage will drop to meet the power supply's output power requirement. Therefore, all of the data taken had a current limit of 5A per converter.

The V_{out} and GND from both demo boards then connect to the second protoboard. The voltage sensors, which are resistor dividers of 75k Ω and 11k Ω , then take in the resistor divider values and are calculated back with the Arduino from which the user can observe the voltages on their PC. Diodes are then placed after the inputs into the protoboard. Then, 10m Ω resistors are used with the INA169 current sensors, in which the voltage outputs of the INA169 are connected to the analog in pins of the Arduino and are converted back into current that the user can observe. Both the voltage sensors and current sensors are observable to the user using serial communication with Arduino. After the current sensors, the two output voltages are then combined into a single output, which has an output of around 12V. The block diagram of the test configuration setup for stage 2 is shown in Figure 5-11.

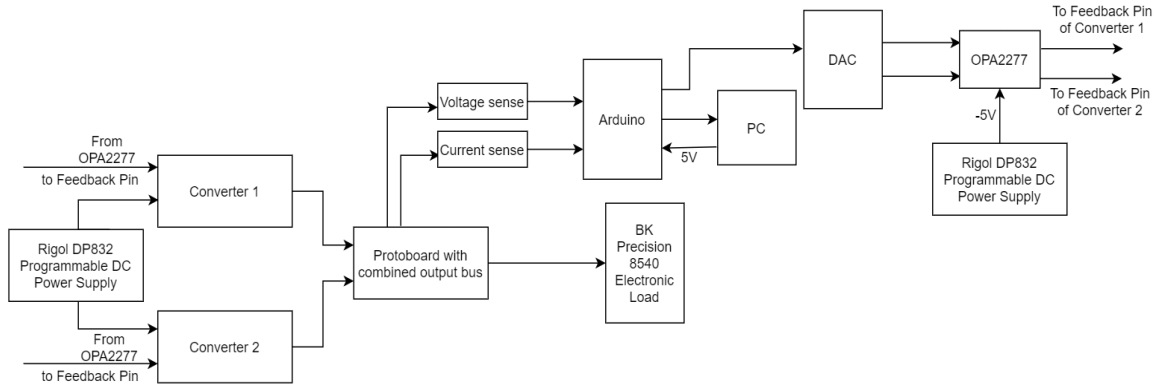


Figure 5-11: Test configuration setup of stage 2.

After testing stage 2, the addition of stage 1 was implemented in conjunction with stage 2. The entire setup, with stage 1 and stage 2 connected, is shown in Figure 5-12.

Figure 5-13 illustrates stage 2, the demo boards in parallel with the protoboard and Arduino. Figure 5-14 shows a closer look of the stage 2 protoboard.

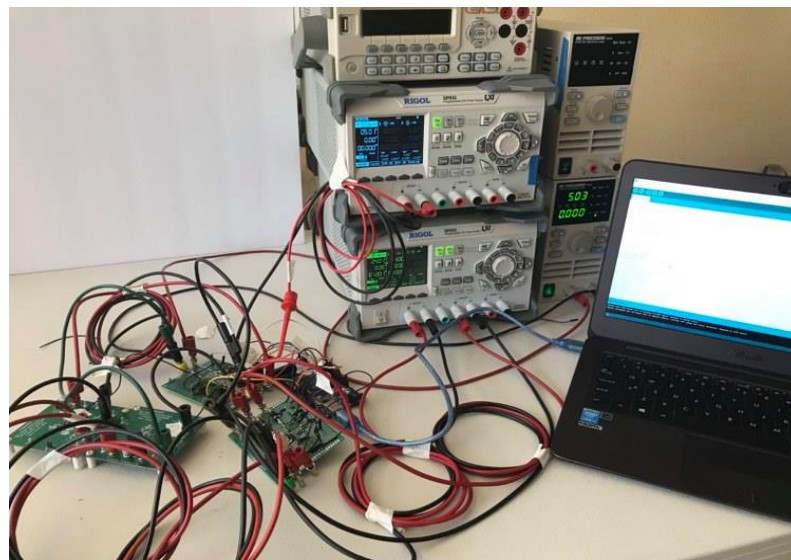


Figure 5-12: Setup of entire circuit.

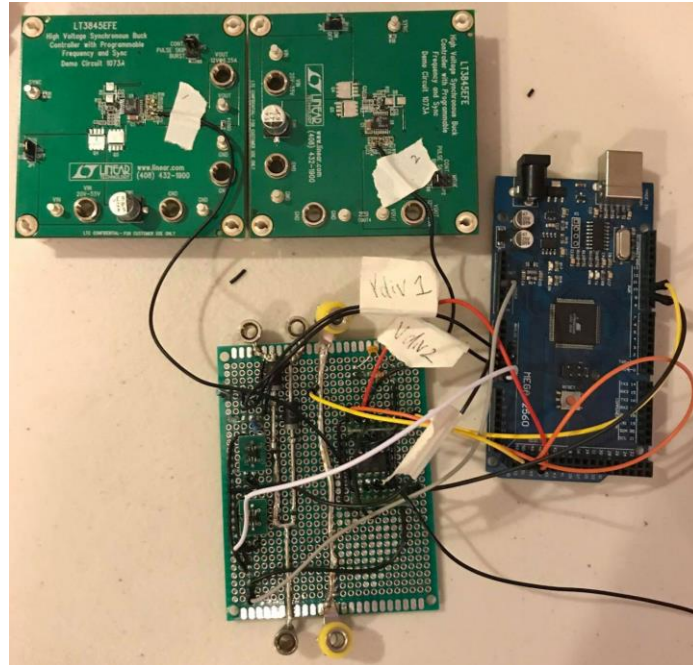


Figure 5-13: Stage 2, demo boards in parallel with protoboard and Arduino.

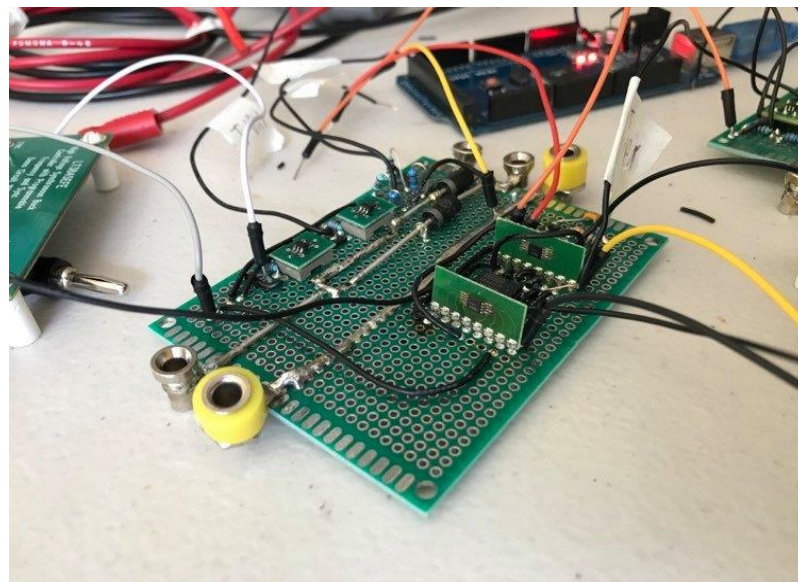


Figure 5-14: Stage 2 protoboard.

The DAC8801 and OPA2277 supplied the small negative voltage to the FB nodes. DAC8801 is a 14-bit DAC that outputs a current and works with the OPA2277 current to voltage amplifier. Both the DAC8801 and OPA2277 are high precision, with little noise or error. This is vital to the purpose of the DAC in this project, as the injected voltage is extremely sensitive in the millivolts range. The OPA2277 outputs a negative voltage, in which the injected voltage and load current percent, which was mentioned previously in Chapter 4, will actually be switched between the two converters. Because of the noise from the long cables to connect from board to board, the DAC code can be slightly inconsistent with its corresponding DAC voltage.

Next, the two stages were then put together and tested. Originally, in Chapter 3, it was stated that only 3A would be used as the output load current. This was changed in Chapter 4, where the output load current was changed from 5A to 7A.

Tables 5-1 and 5-2 list the current split between the two converters, in addition to the efficiencies of the converters at 5A load.

Table 5-1: Uneven Current Splitting and Efficiencies of Converter 1 with 5A Load

Current.

I_{Load} Percentage (%)	V_{in} [V]	I_{in} [A]	V_{out} [V]	I_{out} [A]	Efficiency (%)
0	24.01	0.04	12.84	0	0
10	23.94	0.31	12.67	0.50	85.36
20	23.93	0.57	12.60	1.00	92.37
30	23.92	0.83	12.40	1.50	93.62
40	23.90	1.09	12.25	2.00	94.23
50	23.89	1.34	12.12	2.50	94.65
60	23.89	1.64	12.36	3.00	94.64
70	23.93	1.95	12.58	3.50	94.35
80	23.87	2.28	12.88	4.002	94.71
90	23.88	2.62	13.15	4.50	94.58
100	23.85	2.99	13.54	4.988	94.70

Table 5-2: Uneven Current Splitting and Efficiencies of Converter 2 with 5A Load
Current.

I_{Load} Percentage (%)	V_{in} [V]	I_{in} [A]	V_{out} [V]	I_{out} [A]	Efficiency (%)
100	23.86	2.97	12.82	4.99	90.45
90	23.88	2.57	12.65	4.50	92.75
80	23.87	2.24	12.49	4.00	93.43
70	23.93	1.92	12.30	3.50	93.72
60	23.89	1.61	12.10	2.99	94.25
50	23.89	1.32	11.93	2.50	94.57
40	23.90	1.07	12.18	2.00	95.25
30	23.92	0.81	12.43	1.50	96.23
20	23.93	0.56	12.67	0.99	94.35
10	23.94	0.30	12.93	0.50	90.01
0	24.01	0.06	13.41	0	0

These two tables illustrate the uneven current sharing between the two converters. For example, the column of I_{Load} percentage of converter 1 is 40% illustrating that I_{out} is 2.004A while the column of I_{Load} percentage of converter 2 is 60% illustrating that I_{out} is 2.996A. Note that the total load current for this example is 5A. While testing, there were some inconsistencies with the output voltage of the converters. The DAC provides a small negative voltage at the FB node of the converter, where it was originally grounded.

That varying node is essentially a floating node since the feedback of the converter is not actually referencing ground which is why V_{out} varies slightly. Figure 5-15 illustrates the efficiency versus load current percentage curve for the data in the above tables.

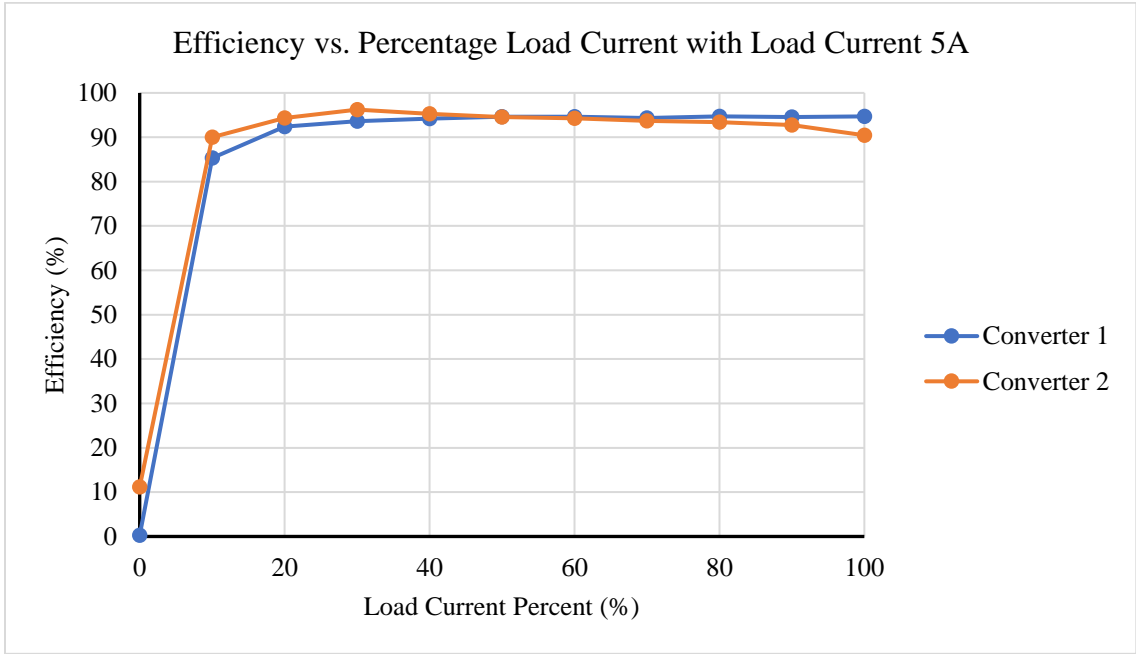


Figure 5-15: Efficiency vs. Percentage load current with 5A load current.

The two curves are close to each other, which means that the two converters have slight dissimilarities. However, even though the efficiencies of the two converters look similar, the differences per current ratio do contribute to differences in total efficiencies.

Because there is no current sensor and voltage sensor at the output of the entire circuit, the efficiency of the system is determined by the following equations.

$$Efficiency_{Total} = \frac{P_{out1} + P_{out2}}{P_{in1} + P_{in2}}$$

$$Efficiency_{Total} = \frac{(V_{out1} \cdot I_{out1}) + (V_{out2} \cdot I_{out2})}{(V_{in1} \cdot I_{in1}) + (V_{in2} \cdot I_{in2})}$$

This equation disregards the voltage diode drop following the converters, as there is no voltage or current sensors at the combined single output. The Arduino will then calculate the total efficiency of each current split ratio. Table 5-3 lists the results of this calculation with load current of 5A which are then graphed as shown in Figure 5-16.

Table 5-3: Total Efficiencies with 5A Load Current.

Load Current Ratio of Converter 1 to Converter 2 (% / %)	Total Efficiency (%)
0/100	89.25
10/90	91.96
20/80	93.22
30/70	93.69
40/60	94.24
50/50	94.61
60/40	94.88
70/30	94.91
80/20	94.64
90/10	94.11
100/0	93.05

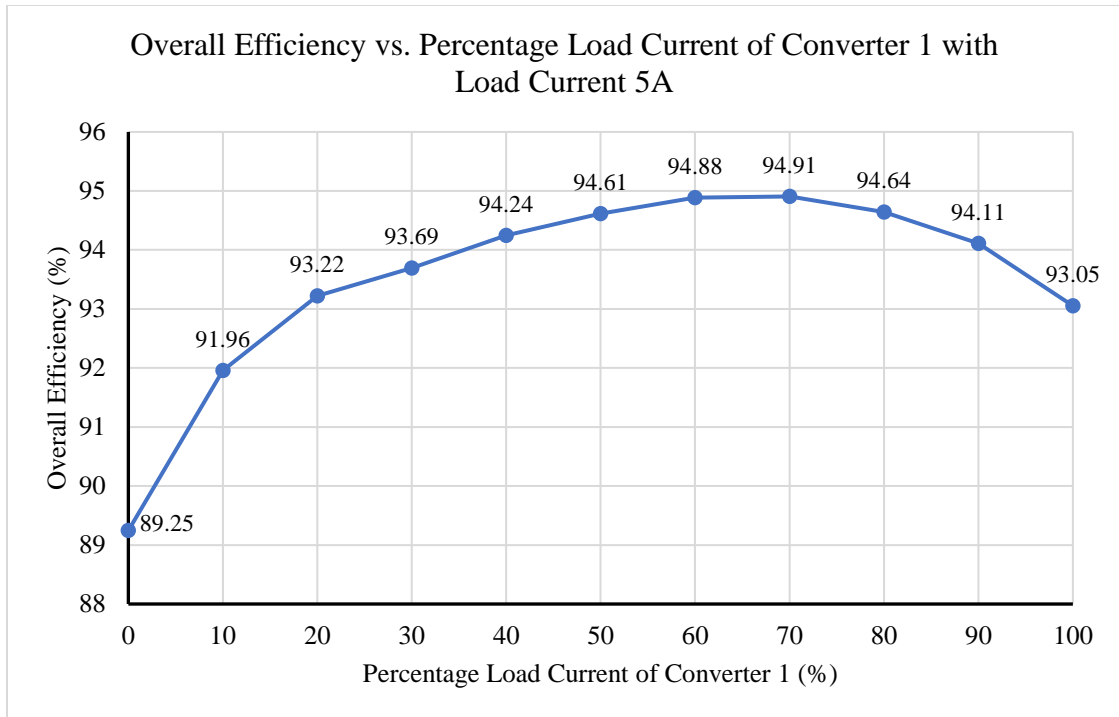


Figure 5-16: Overall efficiency vs. load current percentage of converter 1 with 5A load current.

As evident from Figure 5-16, the current ratio of 70/30 at 5A load current will be most efficient. The Arduino will then alter the DAC value to match the 70/30 current split ratio so that the total efficiency of the system will be at its highest.

Table 5-4 and 5-5 illustrate the uneven current sharing in addition to the efficiencies when the load current is at 6A for converter 1 and converter 2.

Table 5-4: Uneven Current Splitting and Efficiencies of Converter 1 with 6A Load
Current.

I _{Load} Percentage (%)	V _{in} [V]	I _{in} [A]	V _{out} [V]	I _{out} [A]	Efficiency (%)
20	23.92	0.68	12.48	1.19	91.91
30	23.90	0.99	12.27	1.80	93.34
40	23.90	1.29	12.18	2.39	94.73
50	23.91	1.60	11.92	3.00	93.47
60	23.90	1.95	12.24	3.59	94.28
70	23.89	2.34	12.64	4.20	95.05
80	23.90	2.74	12.93	4.80	94.77

Table 5-5: Uneven Current Splitting and Efficiencies of Converter 2 with 6A Load
Current.

I _{Load} Percentage (%)	V _{in} [V]	I _{in} [A]	V _{out} [V]	I _{out} [A]	Efficiency (%)
80	23.90	2.68	12.57	4.80	94.23
70	23.89	2.28	12.27	4.20	94.61
60	23.9	1.92	11.98	3.60	94.03
50	23.91	1.54	11.73	3.00	95.56
40	23.9	1.27	11.94	2.41	94.80
30	23.9	0.96	12.15	1.79	95.10
20	23.92	0.66	12.36	1.20	93.94

Data from Tables 5-4 and 5-5 were then plotted as shown in Figure 5-17. Note that with these sets of data, the load current percentages range from 20% to 80%. This is due to the fact that at any currents higher than 80% of 6A, the converters will run over their current limit of 5A. By the same reasoning, the 7A load test case has data points ranging from 30% to 70%.

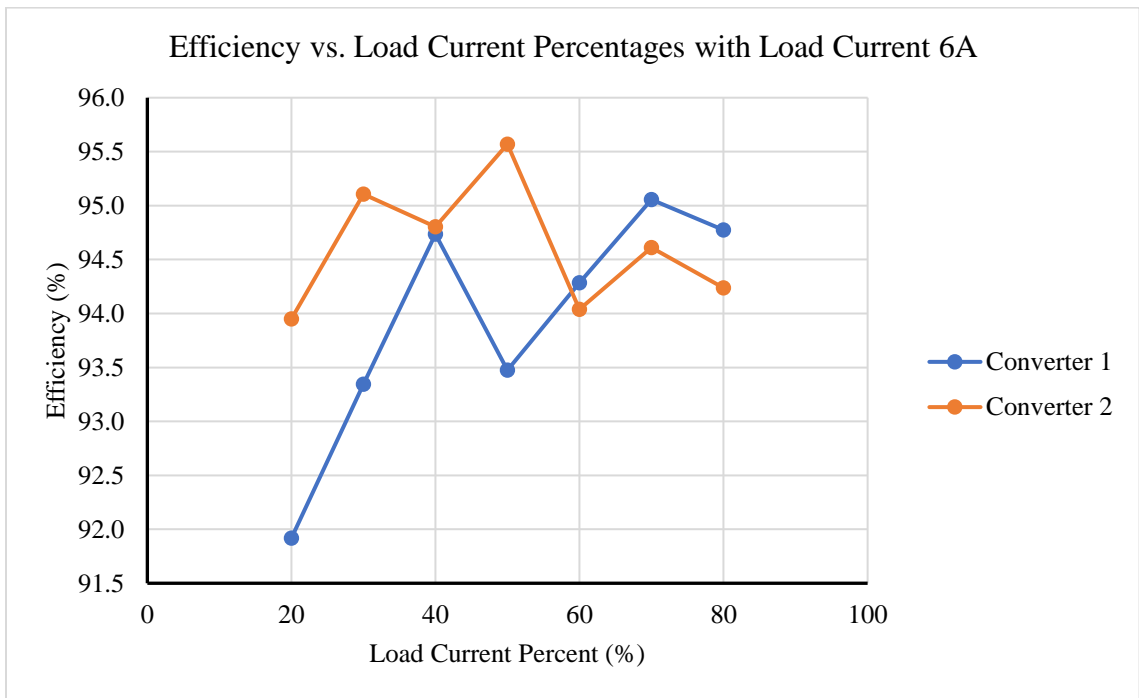


Figure 5-17: Efficiency vs. Percentage load current with 6A load current.

Using the same previous equation, the Arduino code produces the ratio with the highest total efficiency. Table 5-6 and Figure 5-18 illustrate the total efficiencies for each of the different ratios.

Table 5-6: Total Efficiencies with 6A Load Current.

Load Current Ratio of Converter 1 to Converter 2 (% / %)	Total Efficiency (%)
20/80	93.77
30/70	94.23
40/60	94.32
50/50	94.50
60/40	94.49
70/30	95.07
80/20	94.61

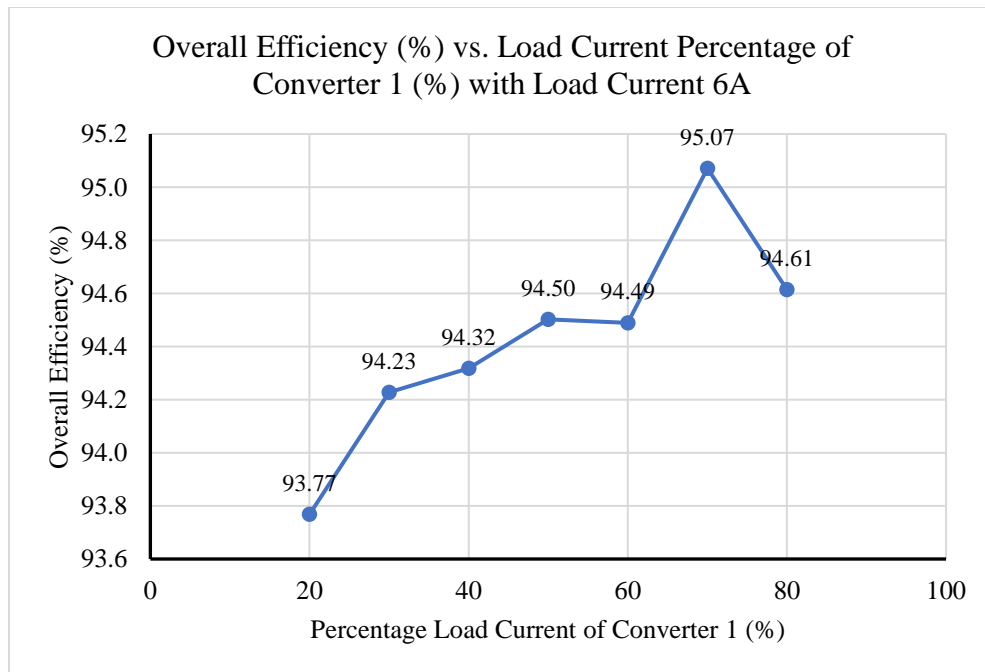


Figure 5-18: Overall efficiency vs. load current percentage of converter 1 with 6A load current.

Clearly, from Table 5-6 and Figure 5-18, the system is most efficient when converter 1 is at 70% of the 6A load current, and when converter 2 is at 30% of the 6A load current. For the 7A load case test, Figure 5-19 illustrates the separate efficiencies of the two converter boards, and Figure 5-20 illustrates the total efficiency of the entire system. As can be observed in Figure 5-20, the most efficient ratio is when converter 1 is 60% of 7A and converter 2 is 40% of 7A.

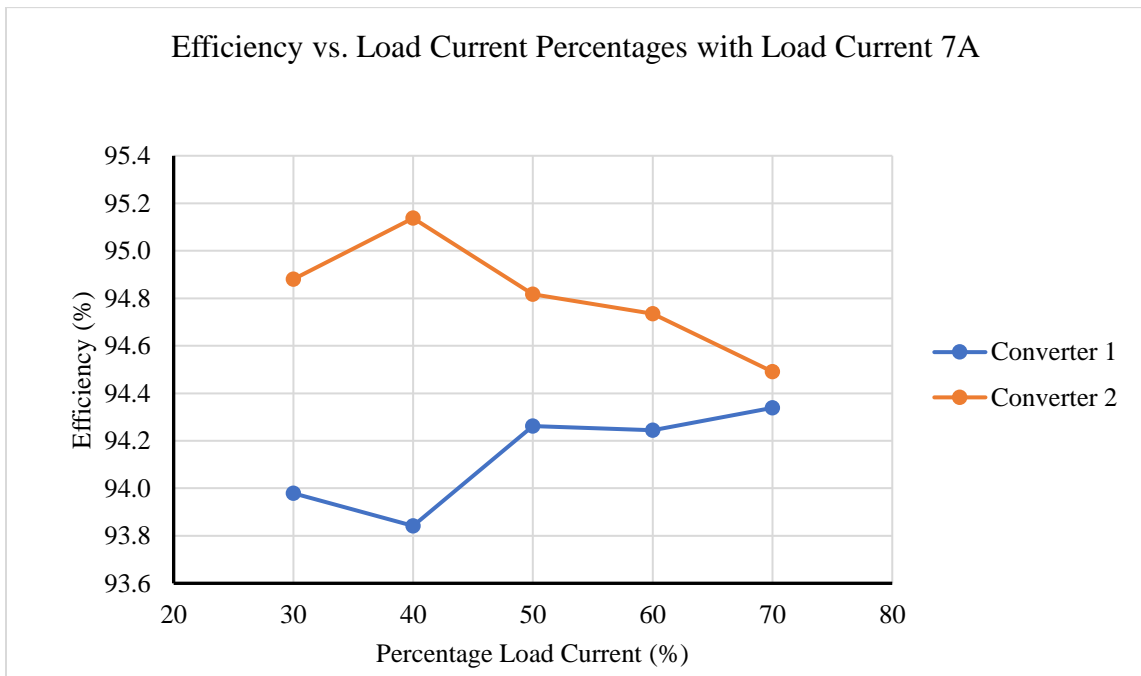


Figure 5-19: Efficiency vs. Percentage load current with 7A load current.

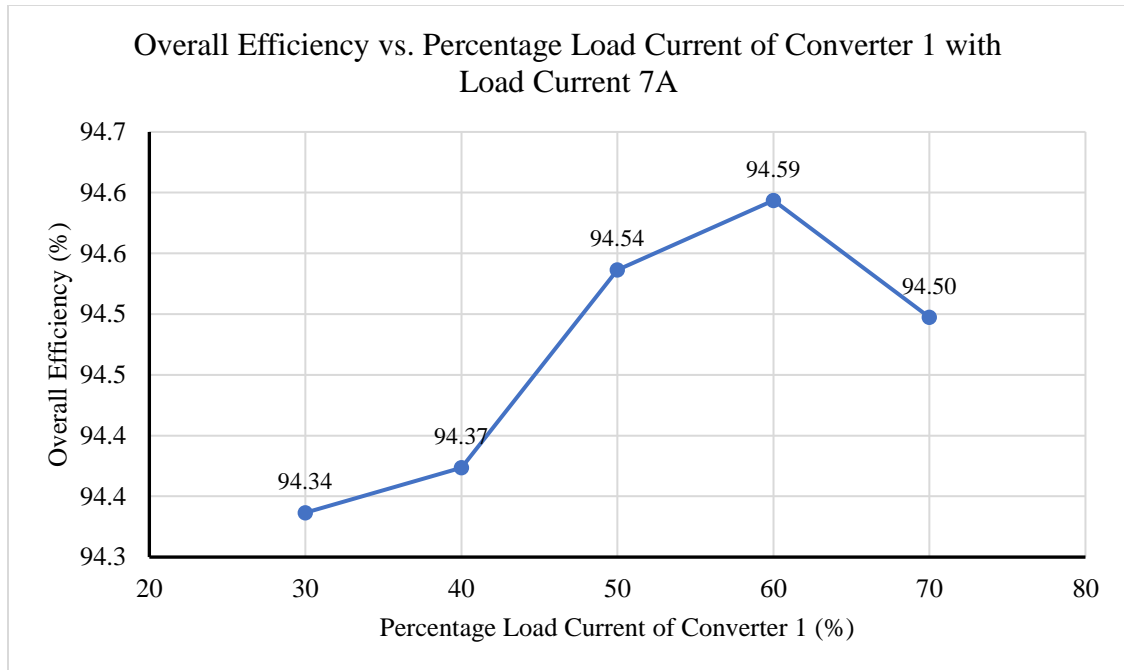


Figure 5-20: Overall efficiency vs. Percentage load current of converter 1 with 7A load current.

One of the most essential parts to be able to make this whole system work is the Arduino. The Arduino code helps to output the different DAC voltage by writing to it through SPI. Each integer that is written from the Arduino code corresponds to a different DAC voltage, in which it splits the load current into different ratios between the two converters. Figure 5-21 depicts the algorithm for finding the ratio that would produce the greatest efficiency. The Arduino uses this algorithm to be able to produce the most efficient system. See the appendix for the complete Arduino code used in this project.

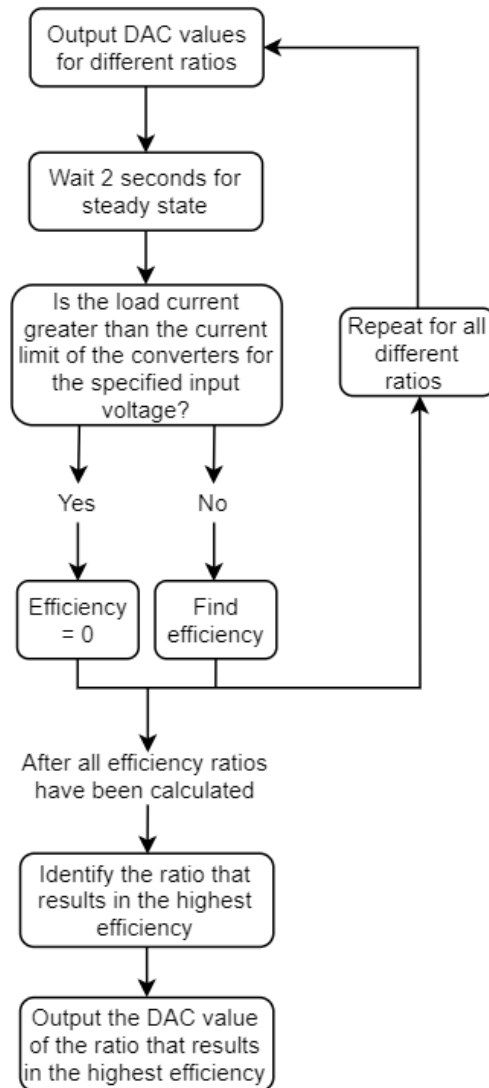


Figure 5-21: Algorithm to find most efficient ratio.

The DAC values for 5A, 6A, and 7A are shown in Figures 5-22, 5-23, and 5-24, respectively. These graphs are all similar in the sense that they are very close to being linear. For converter 1, it starts off with a straight horizontal line at a certain DAC value then progresses into a positive linear graph. For converter 2, it starts off with a negative linear graph then plateaus at 0. For the 5A load current, the average difference between the DAC values of the different ratios is about 562. For the 6A load current, the average difference between the DAC values of the different ratios is about 630. Lastly, for the 7A

load current, the average difference between the DAC values of the different ratios is about 730.

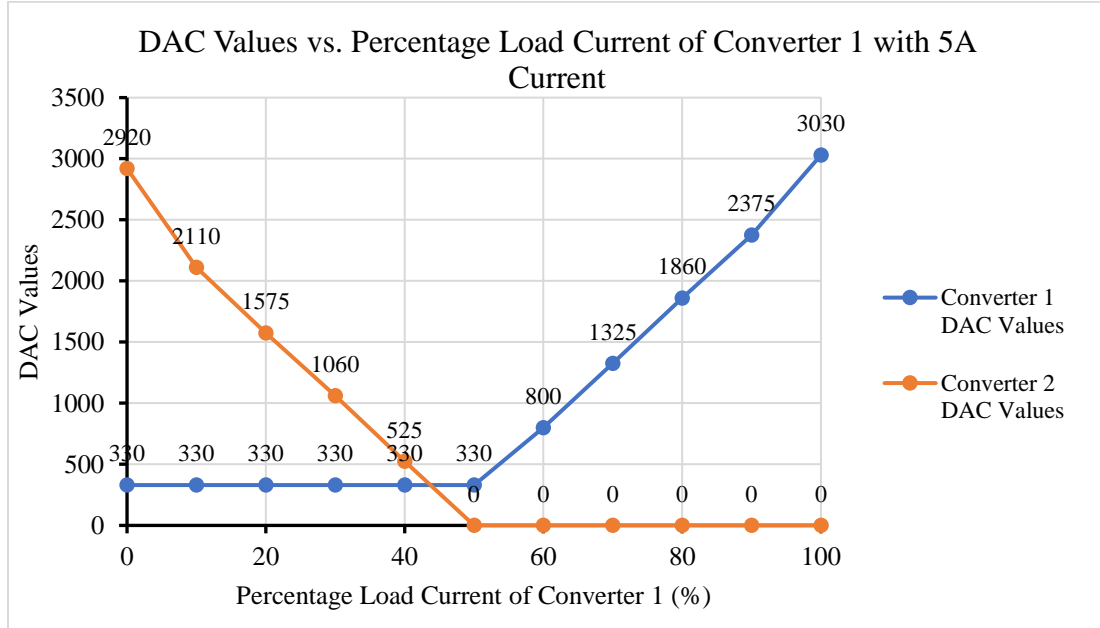


Figure 5-22: DAC values vs. Percentage load current of converter 1 with 5A load current.

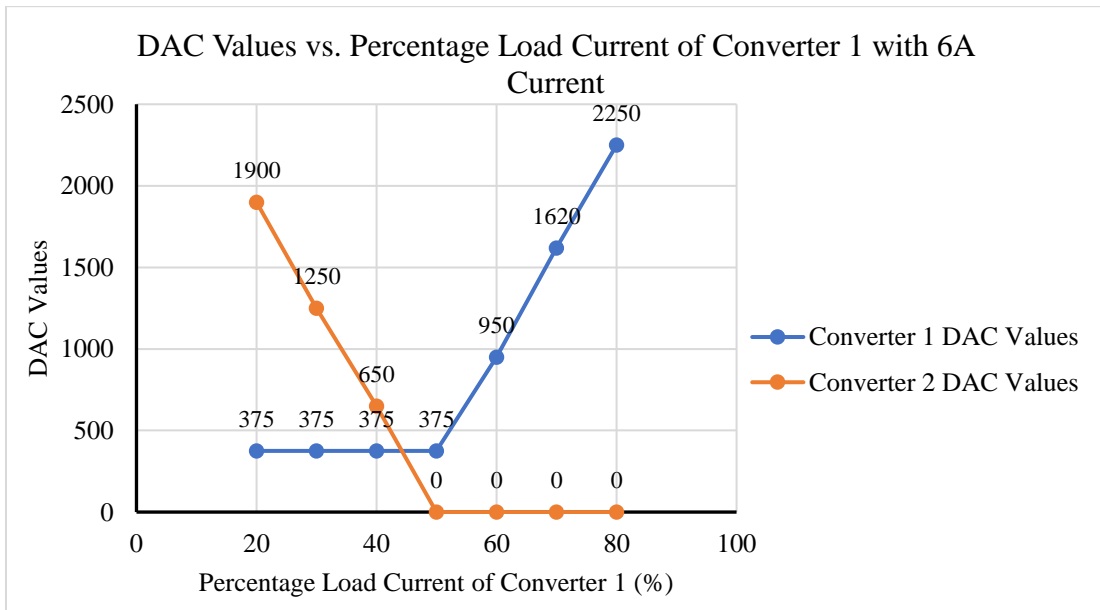


Figure 5-23: DAC values vs. load current percentage of converter 1 with 6A load current.

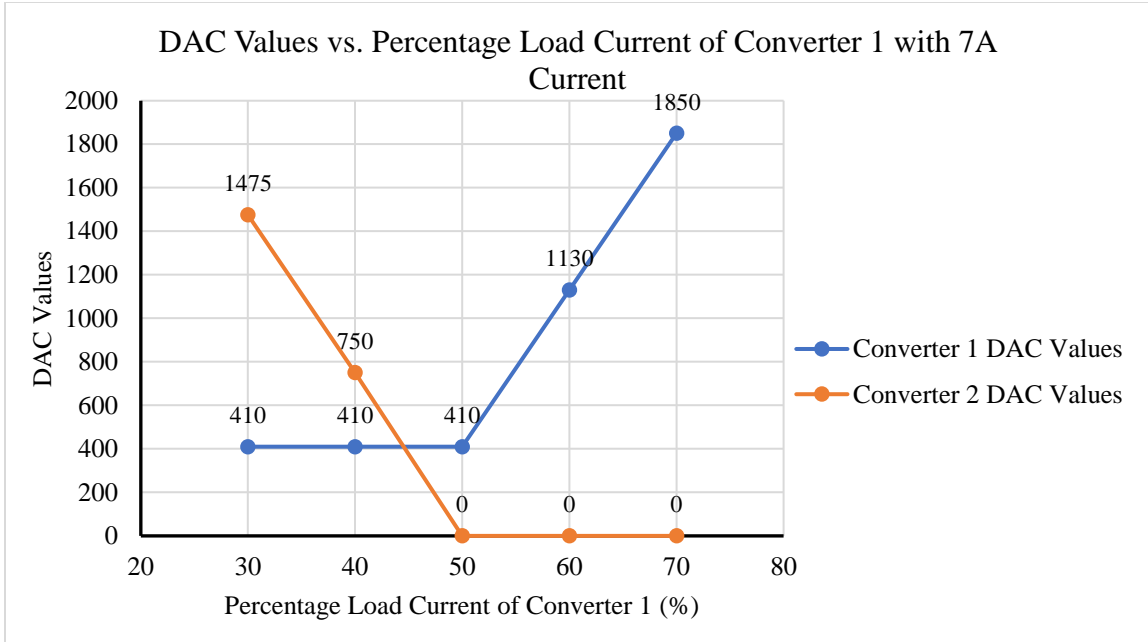


Figure 5-24: DAC values vs. percentage load current of converter 1 with 7A load current.

The reference voltage for the DAC was originally set to be around 1.8V.

However, during testing, it was measured to be 1.56V. This is most likely due to the limited current supplied by the 5V rail on the Arduino. The DAC values can be converted into its corresponding voltage value by the following equation.

$$V_{out} = -V_{ref} \times \frac{(DAC\ Value)}{16384}$$

In conclusion, the hardware tests demonstrate that the two converters in parallel can split current unevenly if an external small negative voltage is applied in place of the ground node of the feedback pins. Different DAC values from the Arduino code resulting in different voltage values are applied to the converters. This in turn enables the provision of different ratios of currents. Being able to characterize the efficiencies of the two converters at varying loads can be very useful, as the user can choose the load current

ratio of the two converters that will be at the highest efficiency for the system. This will further provide the benefit of acquiring more input power delivered to the load.

6. CONCLUSION

This thesis investigates a method of unevenly splitting the load current in a multiple-input single-output converter (MISO) to maximize the overall system efficiency. A system with two buck converters and the associated controllers were designed and built to demonstrate the functionality of the proposed method. The previous versions of MISO converter for the DC House project were all based on equal load sharing current but focused on different aspects of the converter. The proposed unequal current sharing MISO converter was simulated using LTSpice wherein different scenarios of the circuit were tested under various scenarios including a case utilizing converters with identical model and another using slightly different models for both converters. Hardware construction and test were also performed for the proposed system to demonstrate its functionality and performance.

Simulation and hardware test results indicate that unequal load current sharing can be achieved and can be more efficient than the equal current sharing method. To implement the unequal load sharing, a small negative voltage was changed in place of the ground voltage at the feedback node which changes the output voltage slightly. This tiny increase or decrease in output voltage in addition to the difference in output voltages from the two converters is what allows the load current to split unevenly. The converter with the higher output voltage is the converter that will output a higher current. All of the hardware results indicate that equal current sharing between the two converters did not yield the maximum efficiency, and another load ratio would actually yield the greatest efficiency. For the 5A and 6A load current cases, the ratio case of 70% load from converter 1 and 30% load from converter 2 yielded the greatest efficiency of 94.91% and

95.07%, respectively. For the 7A load current, the 60% load from converter 1 and 40% load from converter 2 yielded the greatest efficiency at 94.59%. Additionally, with the Arduino code, the circuit is able to achieve maximum efficiency by comparing all of the efficiencies of the different ratios and changing the DAC value to be able to produce the maximum efficiency. These test cases illustrate that an even load current sharing may not always be the most desired if outputting the greatest efficiency is the goal.

Because this thesis is a proof-of-concept of the proposed unequal sharing MISO converter method, a buck converter was used as it was easier to implement and test. Furthermore, hardware testing would be easier with lower output power rather than using higher output power especially given the limited access and availability of test equipment. However, since the proposed MISO converter will eventually be used in the DC House project, future improvements from the current design should be in place. This includes the use of boost or 4-switch buck-boost converter which are the actual topologies used in the existing MISO. Additionally, the power level should also be increased to at least 250W following the existing MISO converter design. Regardless of the topology used, the controller utilized in the proposed system in this thesis can still be implemented in the future MISO converter development

Other follow up work includes implementing a feedback loop with the Arduino code and the output current sensors. The current code changes the DAC values to specific values previously recorded to be able to unevenly split the current at specific ratios. However, any disturbances may cause DAC voltage differences which could change the output currents drastically. Implementing a feedback loop to continuously increase or

decrease the DAC values until the output current is achieved may be more practical if this were to be implemented in a real DC House system.

Another follow up work could also include adding another path in stage 1 to allow current to flow from the top power path to the bottom power path and ultimately be able to use just converter 2 for the 0% / 100% ratio case. Currently, this thesis only considers one path from the bottom power path to the top power path. If another diode and switch were added to allow current to flow from the top path to the bottom path, the system would be able to add another ratio case that is more accurate. Having both of these options will allow the use of solely converter 1 or converter 2 for the 100% / 0% case and 0% / 100% case.

Lastly, designing a PCB board would be another follow up improvement effort. Designing and using a PCB board would minimize noise and inconsistencies than using a protoboard as there is less room for error if the boards shift.

Ultimately, after the development and study of uneven current sharing, we can conclude that splitting current unevenly between multiple parallel DC-DC converters can achieve a greater efficiency than evenly sharing current between the two converters. Once the ratio case that yields the greatest efficiency is identified, the circuit is able to successfully output the unique DAC voltage values for that specific ratio case.

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APPENDIX A: ARDUINO CODE

```
#include <SPI.h>

//A0-3 for input voltage sense and current sense
//A4-7 for voltage sense and current sense on output of converters

const int slaveSelectPin1 = 9; // CS DAC 1
const int slaveSelectPin2 = 10; // CS DAC 2
const int slaveSelectPin3 = 11; // INP 1
const int slaveSelectPin4 = 12; // INP 2

float eff_0_100;
float eff_1090;
float eff_2080;
float eff_3070;
float eff_4060;
float eff_5050;
float eff_6040;
float eff_7030;
float eff_8020;
float eff_9010;
float eff_100_0;
float checkiout1;
float checkiout2;
float checkvin1;
float checkvin2;
float iout1;
float iout2;
float loadcurrent;

// float currentlimits[number of items in array] = {0,1,2,3,4,5,6,...};
// currentlimits[0]=0;
float currentlimits[8] = {3.95,4.10,4.30,4.50,4.70,4.85,5.0,5.20};

float overcurrentlimit;
float overcurrent;
int index_max;
float maximum;

void setup() {
  //serial connection setup
  //opens serial port, sets data rate to 9600 bps
  Serial.begin(9600);
  pinMode(slaveSelectPin1, OUTPUT);
  pinMode(slaveSelectPin2, OUTPUT);
  pinMode(slaveSelectPin3, OUTPUT);
  pinMode(slaveSelectPin4, OUTPUT);
  // set to CS to low (it's high because it's CS not)
  digitalWrite(slaveSelectPin1, HIGH); //off
  digitalWrite(slaveSelectPin2, HIGH); //off
  digitalWrite(slaveSelectPin3, LOW); //off
  digitalWrite(slaveSelectPin4, HIGH); //on
  SPI.begin();
}
```



```

void loop() {
  {
    delay(2000); //wait 2 sec

    ///////////////////////////////////////////////////////////////////
    // conv1 50/ conv2 50

    // apply 50%/50% to injected voltage
    DACwrite(375,0);
    delay(2000); //wait 2 sec
    overcurrent = checklimits();

    if (overcurrent == 1) {
      DACwrite(375,0);
      eff_5050 = 0;
      Serial.println("Total Efficiency of 50/50: ");
      Serial.println(eff_5050);
      Serial.println("-----");
    }
    else if (overcurrent == 0) {
      // wait 5 sec for circuit to reach steady state
      delay(5000);
      eff_5050 = efficiency();
      Serial.println("Total Efficiency of 50/50: ");
      Serial.println(eff_5050);
      Serial.println("-----");
    }
  }

  ///////////////////////////////////////////////////////////////////
  ///////////////////////////////////////////////////////////////////
  // conv1 60/ conv2 40

  // apply 60%/40% to injected voltage
  DACwrite(950,0);

  overcurrent = checklimits();

  if (overcurrent == 1) {
    DACwrite(375,0);
    eff_6040 = 0;
    Serial.println("Total Efficiency of 60/40: ");
    Serial.println(eff_6040);
    Serial.println("-----");
  }
  else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_6040 = efficiency();
    Serial.println("Total Efficiency of 60/40: ");
    Serial.println(eff_6040);
    Serial.println("-----");
  }
}

/////////////////////////////////////////////////////////////////

```

```

////////////////////////////////////
// conv1 70/ conv2 30

// apply 70%/30% to injected voltage
DACwrite(1620,0);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(1620,0);
    eff_7030 = 0;
    Serial.println("Total Efficiency of 70/30: ");
    Serial.println(eff_7030);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_7030 = efficiency();
    Serial.println("Total Efficiency of 70/30: ");
    Serial.println(eff_7030);
    Serial.println("-----");
}

////////////////////////////////////
////////////////////////////////////
// conv1 80/ conv2 20

// apply 80%/20% to injected voltage
DACwrite(2250,0);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(2250,0);
    eff_8020 = 0;
    Serial.println("Total Efficiency of 80/20: ");
    Serial.println(eff_8020);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_8020 = efficiency();
    Serial.println("Total Efficiency of 80/20: ");
    Serial.println(eff_8020);
    Serial.println("-----");
}

////////////////////////////////////

```

```

////////////////////////////////////
// conv1 90/ conv2 10

// apply 90%/10% to injected voltage
DACwrite(2700,0);

overcurrent = checklimits();

if (overcurrent == 1) {
  DACwrite(375,0);
  eff_9010 = 0;
  Serial.println("Total Efficiency of 90/10: ");
  Serial.println(eff_9010);
  Serial.println("-----");
}
else if (overcurrent == 0) {
  // wait 5 sec for circuit to reach steady state
  delay(5000);
  eff_9010 = efficiency();
  Serial.println("Total Efficiency of 90/10: ");
  Serial.println(eff_9010);
  Serial.println("-----");
}

////////////////////////////////////
////////////////////////////////////
//conv1 100/ conv2 0

// just adding the currents
DACwrite(375,0);
delay(1000);
iout1 = analogRead(A5)*(50.00/40.0)*(5.0/1024.0);
iout2 = analogRead(A7)*(50.00/40.0)*(5.0/1024.0);

loadcurrent = iout1 + iout2;

float vin1 = analogRead(A0)*(86.00/11.0)*(5.0/1024.0);
float vin2 = analogRead(A2)*(86.00/11.0)*(5.0/1024.0);

//want to cap it at 6A per converter to make sure it doesn't blow
if ((vin1 >= 23.8) || (vin2 >= 23.8)) {
  if (loadcurrent > 6) {
    Serial.println("Load current greater than 6A, cannot solely use Conv 1.
Back to 50/50.");
    DACwrite(375,0);
    eff_100_0 = 0;
    Serial.println("Total Efficiency of 100/0: ");
    Serial.println(eff_100_0);
    Serial.println("-----");
  }
  else {
    digitalWrite(slaveSelectPin4, LOW); //off
    digitalWrite(slaveSelectPin3, HIGH); //on
  }
}

```

```

// apply 100%/0% to injected voltage
DACwrite(375,0);

delay(5000); //wait 5 sec to reach steady state
eff_100_0 = efficiency();
Serial.println("Total Efficiency of 100/0: ");
Serial.println(eff_100_0);
Serial.println("-----");
}
}
else if ((vin1 >= 19.8 && vin1 <= 23.2) || (vin2 >= 19.8 && vin2 <= 23.2))
{
    if (loadcurrent > 5) {
        Serial.println("Load current greater than 5A, cannot solely use Conv
1. Back to 50/50.");
        DACwrite(375,0);
        eff_100_0 = 0;
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
    else {
        digitalWrite(slaveSelectPin3, HIGH); //on
        digitalWrite(slaveSelectPin4, LOW); //off
        // apply 100%/0% to injected voltage
        DACwrite(375,0);

        delay(5000); //wait 5 sec to reach steady state
        eff_100_0 = efficiency();
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
}
else if ((vin1 >= 17.8 && vin1 <= 19.2) || (vin2 >= 17.8 && vin2 <= 19.2))
{
    if (loadcurrent > 4) {
        Serial.println("Load current greater than 4A, cannot solely use Conv
1. Back to 50/50.");
        DACwrite(375,0);
        eff_100_0 = 0;
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
    else {
        digitalWrite(slaveSelectPin3, HIGH); //on
        digitalWrite(slaveSelectPin4, LOW); //off
        // apply 100%/0% to injected voltage
        DACwrite(375,0);

        delay(5000); //wait 5 sec to reach steady state
        eff_100_0 = efficiency();
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);

```

```

        Serial.println("-----");
    }
}
/////////////////////////////////////////////////////////////////

/////////////////////////////////////////////////////////////////
// conv1 40/ conv2 60

// apply 40%/60% to injected voltage
DACwrite(375,650);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(375,0);
    eff_4060 = 0;
    Serial.println("Total Efficiency of 40/60: ");
    Serial.println(eff_4060);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_4060 = efficiency();
    Serial.println("Total Efficiency of 40/60: ");
    Serial.println(eff_4060);
    Serial.println("-----");
}

/////////////////////////////////////////////////////////////////

/////////////////////////////////////////////////////////////////
// conv1 30/ conv2 70

// apply 30%/70% to injected voltage
DACwrite(375,1250);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(375,0);
    eff_3070 = 0;
    Serial.println("Total Efficiency of 30/70: ");
    Serial.println(eff_3070);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_3070 = efficiency();
    Serial.println("Total Efficiency of 30/70: ");
    Serial.println(eff_3070);
    Serial.println("-----");
}
}

```

```

/////////////////////////////////////////////////////////////////

/////////////////////////////////////////////////////////////////
// conv1 20/ conv2 80

// apply 20%/80% to injected voltage
DACwrite(375,1900);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(375,0);
    eff_2080 = 0;
    Serial.println("Total Efficiency of 20/80: ");
    Serial.println(eff_2080);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_2080 = efficiency();
    Serial.println("Total Efficiency of 20/80: ");
    Serial.println(eff_2080);
    Serial.println("-----");
}

/////////////////////////////////////////////////////////////////

/////////////////////////////////////////////////////////////////
// conv1 10/ conv2 90

// apply 10%/90% to injected voltage
DACwrite(375,2500);

overcurrent = checklimits();

if (overcurrent == 1) {
    DACwrite(375,2500);
    eff_1090 = 0;
    Serial.println("Total Efficiency of 10/90: ");
    Serial.println(eff_1090);
    Serial.println("-----");
}
else if (overcurrent == 0) {
    // wait 5 sec for circuit to reach steady state
    delay(5000);
    eff_1090 = efficiency();
    Serial.println("Total Efficiency of 10/90: ");
    Serial.println(eff_1090);
    Serial.println("-----");
}

/////////////////////////////////////////////////////////////////

```

```

////////////////////////////////////
// conv1 0/ conv2 100

//want to cap it at 6A per converter to make sure it doesn't blow
if ((vin1 >= 23.8) || (vin2 >= 23.8)) {
    if (loadcurrent > 6) {
        Serial.println("Load current greater than 6A, cannot solely use Conv 2.
Back to 50/50.");
        DACwrite(375,0);
        eff_100_0 = 0;
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
    else {
        // apply 0%/100% to injected voltage
        DACwrite(375,3000);

        delay(5000); //wait 5 sec to reach steady state
        eff_100_0 = efficiency();
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
}
else if ((vin1 >= 19.8 && vin1 <= 23.2) || (vin2 >= 19.8 && vin2 <= 23.2))
{
    if (loadcurrent > 5) {
        Serial.println("Load current greater than 5A, cannot solely use Conv
2. Back to 50/50.");
        DACwrite(375,0);
        eff_100_0 = 0;
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
    else {
        // apply 0%/100% to injected voltage
        DACwrite(375,3000);

        delay(5000); //wait 5 sec to reach steady state
        eff_100_0 = efficiency();
        Serial.println("Total Efficiency of 100/0: ");
        Serial.println(eff_100_0);
        Serial.println("-----");
    }
}
else if ((vin1 >= 17.8 && vin1 <= 19.2) || (vin2 >= 17.8 && vin2 <= 19.2))
{
    if (loadcurrent > 4) {
        Serial.println("Load current greater than 4A, cannot solely use Conv
2. Back to 50/50.");
        DACwrite(375,0);
        eff_100_0 = 0;
        Serial.println("Total Efficiency of 100/0: ");

```

```

        Serial.println(eff_100_0);
        Serial.println("-----");
    }
    else {
        // apply 0%/100% to injected voltage
        DACwrite(375,3000);
    }
}

float eff_array[11] = {eff_0_100, eff_1090, eff_2080, eff_3070, eff_4060,
eff_5050, eff_6040, eff_7030, eff_8020, eff_9010, eff_100_0};

maximum = 0.0;
for (int i=0; i<11; i++) {
    if (eff_array[i] > maximum) {
        maximum = eff_array[i];
        index_max = i;
    }
}

Serial.println("Highest efficiency: ");
Serial.println(maximum);
Serial.println("-----");
if (index_max == 0) {
    Serial.println("Ratio is 0/100");
}
else if (index_max == 1) {
    Serial.println("Ratio is 10/90");
}
else if (index_max == 2) {
    Serial.println("Ratio is 20/80");
}
else if (index_max == 3) {
    Serial.println("Ratio is 30/70");
}
else if (index_max == 4) {
    Serial.println("Ratio is 40/60");
}
else if (index_max == 5) {
    Serial.println("Ratio is 50/50");
}
else if (index_max == 6) {
    Serial.println("Ratio is 60/40");
}
else if (index_max == 7) {
    Serial.println("Ratio is 70/30");
}
else if (index_max == 8) {
    Serial.println("Ratio is 80/20");
}
else if (index_max == 9) {
    Serial.println("Ratio is 90/10");
}
else if (index_max == 10) {

```



```

// check for if conv1 or conv2 has 5.1A or more going through
checkiout1 = analogRead(A5)*(50.00/40.0)*(5.0/1024.0);
checkiout2 = analogRead(A7)*(50.00/40.0)*(5.0/1024.0);
checkvin1 = analogRead(A0)*(86.00/11.0)*(5.0/1024.0);
checkvin2 = analogRead(A3)*(86.0/011.0)*(5.0/1024.0);

if ((checkvin1 >= 24.8) || (checkvin2 >= 24.8)) {
  if (checkiout1 > currentlimits[7] || checkiout2 > currentlimits[7]) {
    Serial.println("Over ");
    Serial.println(currentlimits[7]);
    Serial.println(" A.");
    DACwrite(375,0);
    return overcurrentlimit = 1;
  }
  else {
    return overcurrentlimit = 0;
  }
}
else if ((checkvin1 >= 23.8 && checkvin1 <= 24.2) || (checkvin2 >= 23.8 &&
checkvin2 <= 24.2)) {
  if (checkiout1 > currentlimits[6] || checkiout2 > currentlimits[6]) {
    Serial.println("Over ");
    Serial.println(currentlimits[6]);
    Serial.println(" A.");
    DACwrite(375,0);
    return overcurrentlimit = 1;
  }
  else {
    return overcurrentlimit = 0;
  }
}
else if ((checkvin1 >= 22.8 && checkvin1 <= 23.2) || (checkvin2 >= 22.8 &&
checkvin2 <= 23.2)) {
  if (checkiout1 > currentlimits[5] || checkiout2 > currentlimits[5]) {
    Serial.println("Over ");
    Serial.println(currentlimits[5]);
    Serial.println(" A.");
    DACwrite(375,0);
    return overcurrentlimit = 1;
  }
  else {
    return overcurrentlimit = 0;
  }
}
else if ((checkvin1 >= 21.8 && checkvin1 <= 22.2) || (checkvin2 >= 21.8 &&
checkvin2 <= 22.2)) {
  if (checkiout1 > currentlimits[4] || checkiout2 > currentlimits[4]) {
    Serial.println("Over ");
    Serial.println(currentlimits[4]);
    Serial.println(" A.");
    DACwrite(375,0);
    return overcurrentlimit = 1;
  }
  else {
    return overcurrentlimit = 0;
  }
}

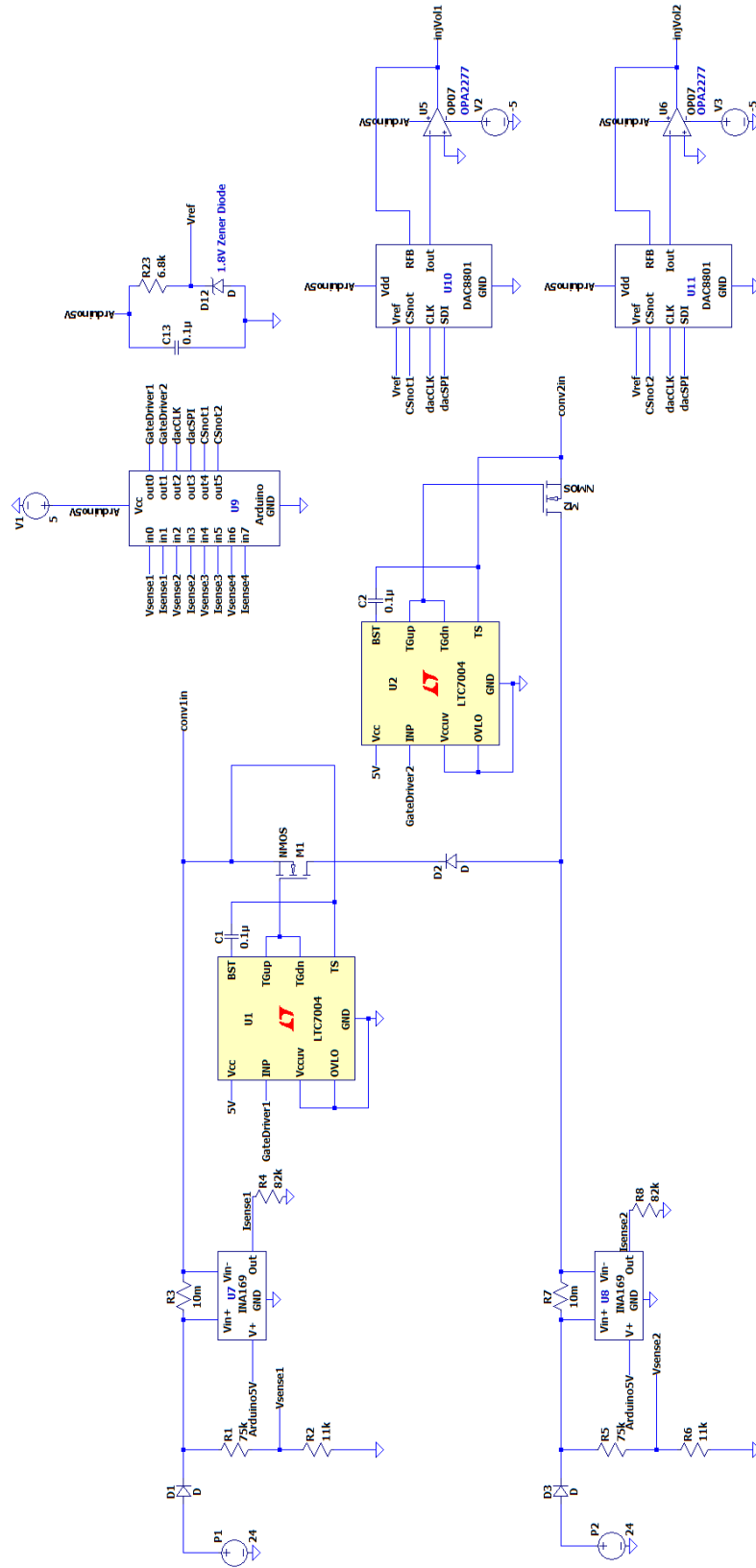
```

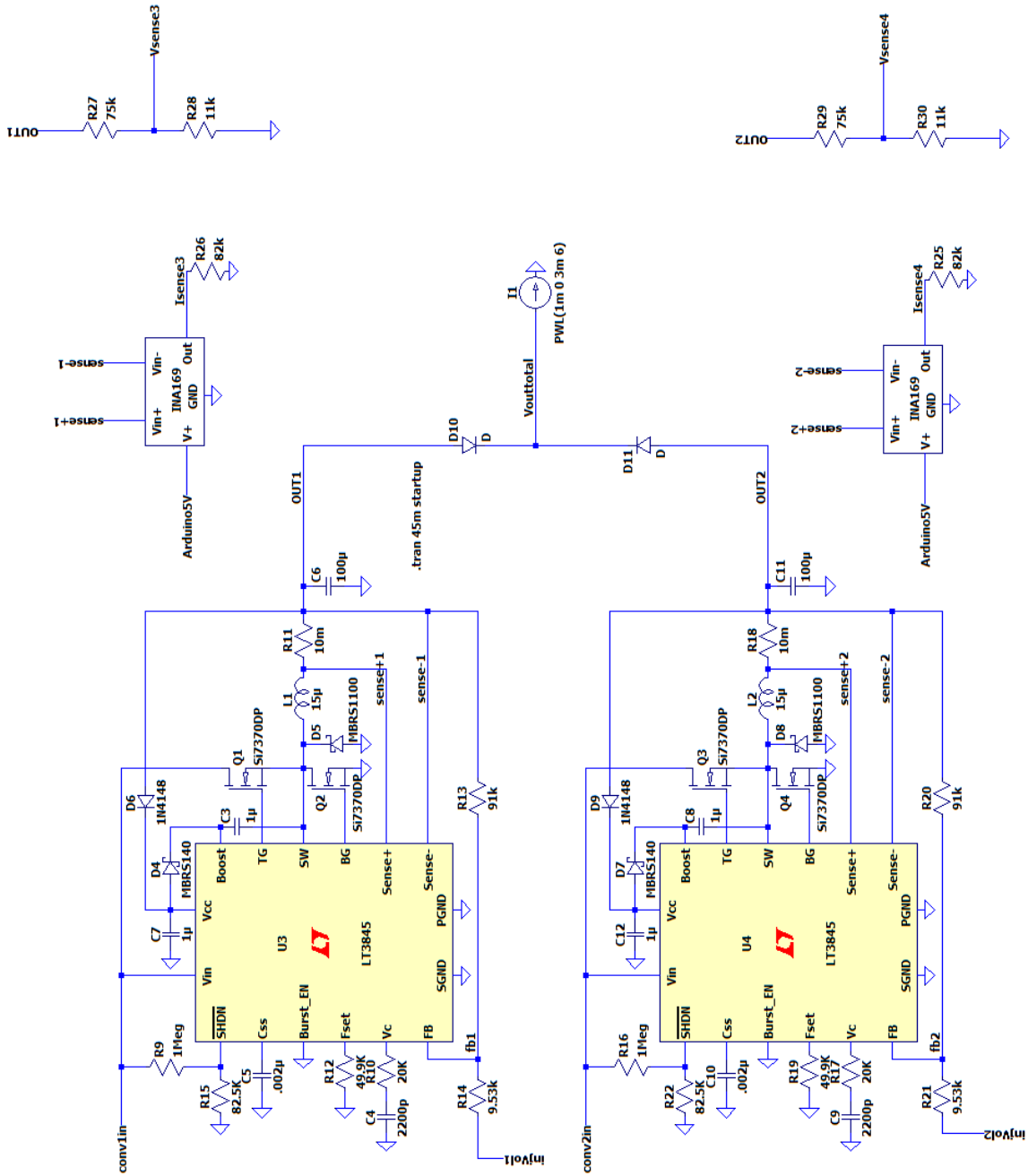
```

    }
  }
  else if ((checkvin1 >= 20.8 && checkvin1 <= 21.2) || (checkvin2 >= 20.8 &&
checkvin2 <= 21.2)) {
    if (checkiout1 > currentlimits[3] || checkiout2 > currentlimits[3]) {
      Serial.println("Over ");
      Serial.println(currentlimits[3]);
      Serial.println(" A.");
      DACwrite(375,0);
      return overcurrentlimit = 1;
    }
    else {
      return overcurrentlimit = 0;
    }
  }
  else if ((checkvin1 >= 19.8 && checkvin1 <= 20.2) || (checkvin2 >= 19.8 &&
checkvin2 <= 20.2)) {
    if (checkiout1 > currentlimits[2] || checkiout2 > currentlimits[2]) {
      Serial.println("Over ");
      Serial.println(currentlimits[2]);
      Serial.println(" A.");
      DACwrite(375,0);
      return overcurrentlimit = 1;
    }
    else {
      return overcurrentlimit = 0;
    }
  }
  else if ((checkvin1 >= 18.8 && checkvin1 <= 19.2) || (checkvin2 >= 18.8 &&
checkvin2 <= 19.2)) {
    if (checkiout1 > currentlimits[1] || checkiout2 > currentlimits[1]) {
      Serial.println("Over ");
      Serial.println(currentlimits[1]);
      Serial.println(" A.");
      DACwrite(375,0);
      return overcurrentlimit = 1;
    }
    else {
      return overcurrentlimit = 0;
    }
  }
  else if ((checkvin1 >= 17.8 && checkvin2 <= 18.2) || (checkvin1 >= 17.8 &&
checkvin2 <= 18.2)) {
    if (checkiout1 > currentlimits[0] || checkiout2 > currentlimits[0]) {
      Serial.println("Over ");
      Serial.println(currentlimits[0]);
      Serial.println(" A.");
      DACwrite(375,0);
      return overcurrentlimit = 1;
    }
    else {
      return overcurrentlimit = 0;
    }
  }
}
}

```

APPENDIX B: SCHEMATIC





*The voltage inVvol1 and inVvol2 will change depending on the ratio desired

APPENDIX C: BILL OF MATERIALS

Designator	Values	Package size	Description	Part Number	Manufacturer	Cost
D1	-	DO-201AA, DO-27, Axial	DIODE SCHOTTKY 45V 8A AXIAL	80SQ045NRLG	ON Semiconductor	0.69
D3						0.69
D2						0.69
D10						0.69
D11						0.69
R1	75k	Through Hole	75 kOhms \pm 1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	MFR-25F52-75K	Yageo	0.1
R5						0.1
R27						0.1
R29						0.1
M1	-	8-SOIC	N-Channel 40V 10A (Ta) 1.7W (Ta) Surface Mount 8-SOIC	AO4484	Alpha and Omega	0.5
M2						0.5
8-SOIC breakout board	-	-	Adafruit SMT Breakout PCB for SOIC-8, 6-pack	-	Adafruit	6.24
8-SOIC breakout board						
8-SOIC breakout board						
8-SOIC breakout board						
R2	11k	Through Hole	RES 11K OHM 1/4W 1% AXIAL	RNF14FTD11K0	Stackpole Electronics	0.1
R6						0.1
R28						0.1
R30						0.1
R4	82k	Through Hole	RES 82K OHM 1/4W 1% AXIAL	RNM14FTC82K0	Stackpole Electronics	0.1
R8						0.1
R26						0.1
R25						0.1
R3	10m	1206	RES 0.01 OHM 1% 1W 1206	ERJ-8B WFR010V	Panasonic Electronic Components	0.66
R7						0.66

U7						2.51
U8	-	SOT-23	IC CURRENT MONITOR 0.5% SOT23-5	INA169NA	Texas Instruments	2.51
U12						2.51
U13						2.51
SOT-23 breakout board						
SOT-23 breakout board	-	-	NKC Electronics SMD SOT-23 to DIP Adapter 0.95mm, 10-pack	-	NKC Electronics	6.95
SOT-23 breakout board						
SOT-23 breakout board						
SOT-23 breakout board						
C1	0.1u	Through Hole	CAP CER 0.1UF 50V Z5U RADIAL	C315C104M5U5TA7303	Kemet	0.24
C2						0.24
C13						0.24
R24	10k	Through Hole	RES 10K OHM 1/4W 1% AXIAL	MFR-25FBF52-10K	Yageo	0.1
R31						0.1
D12	-	SOD-123	DIODE ZENER 1.8V 500MW SOD123	MMSZ4678T1G	ON Semiconductor	0.21
R23	6.8k	Through Hole	RES 6.8K OHM 1/2W 5% CF MINI	CFM12JT6K80	Stackpole	0.1
U1	-	10-TFSOP, 10-MSOP (0.118", 3.00mm Width) Exposed Pad	IC GATE DRVR HIGH-SIDE 10MSOP	LTC7004EMSE#PBF	LT/ADI	5.11
U2						5.11
10-MSOP breakout board	-	-	NKC Electronics SMD MSOP-10 to DIP Adapter, 10-pack	-	NKC Electronics	6.95
10-MSOP breakout board						
U10	-	8-TSSOP, 8-MSOP (0.118", 3.00mm Width)	IC DAC 14BIT A-OUT 8VSSOP	DAC8801IDGKT	Texas Instruments	11.08
U11						11.08

U5	-	8DIP	IC OPAMP GP 2 CIRCUIT 8DIP	OPA2277PA	Texas Instruments	5.04
U6	-					5.04
U9	-	-	Arduino Mega	-	Arduino	11.98
R14	9.53k	0402	RES SMD 9.53K OHM 1% 1/10W 0402	ERJ-2RKF9531X	Panasonic Electronic Components	0.1
R21						0.1
R13	91k	0402	RES SMD 91K OHM 1% 1/10W 0402	ERJ-2RKF9102X	Panasonic Electronic Components	0.1
R20						0.1
Protoboards	-	-	17 PCS DOUBLE SIDED PCB BOARD PROTOTYPE KIT	-	Paxcoo	8.99
100 Header Pins	-	-	MCIGICM 10PCS MALE HEADER PIN, 40 PIN HEADER STRIP (2.54 MM) FOR ARDUINO CONNECTOR	-	MCIGICM	4.99
					Total	107.20