Variable DC Voltage Wall Outlet
for The DC House Project

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Abstract

This senior project report will focus on explaining the design and operation of a variable DC wall outlet for use in the DC house. Testing will include the use of various loads using different input DC voltages not exceeding a maximum output of 90W.

The most important aspects of the outlet are to have a highly-efficient converter efficiency as well as system isolation from the main DC bus on the input. This report will outline the purpose and way of achieving isolation through use of a Flyback DC-DC converter. The user interface is the second significant aspect and details of the plug connection will be detailed along with aspects of how output voltage is selected.

Results from the finished project show that the design used does not support the load requirements on the converter. Although the variable output voltage is achieved, once the output is loaded the switches reach thermal breakdown. Recommendations for improvement of the design will be presented.

I. Introduction

Since the late 1880's and the so-called "War of Currents," distribution of power has been dominated by alternating current (AC). Reasons for settling on AC were numerous, as at the time, significant numbers of loads on the user end needed alternating current for powering devices like motors and other rotary machines. In addition, with the invention of multi-phase rotary machines and transformers, the ability to transmit power long distances become simpler and more cost effective. Using alternating current with transformers, voltage could be stepped up high enough to reduce line losses in the transmission lines. Furthermore, the AC system could transmit higher power using rotary generators driven by large turbines, which at that time were primarily water-driven (hydroelectric). However, one main disadvantage of using AC transmission includes the cost of lines. In a three-phase system, at minimum, three conductors must be used to transmit power. One other disadvantage is the need to monitor power quality (power factor), which inherently affects the efficiency of the system and can cause disruptions in service if not properly maintained.

With the development of photovoltaic systems, large and small, the use of DC distribution is gaining momentum once again. Modern devices controlling inversion of DC power from AC incur costs through inefficiencies throughout the system; so for example, a house powered completely by DC theoretically eliminates losses created during the inversion. Furthermore, in areas that are far from transmission lines, the costs of installing infrastructure to transmit AC power to these remote areas become very great, thus leading to the need for localized power generation and distribution. Photovoltaic panels make the most sense in these cases, as it eliminates the need for costly fuel for generators and regular maintenance on said machines. The benefit of this local distribution system is the removal of the need to transmit power from a distant source. A possible drawback is the necessity for the local populace to be in control of their own distribution, as well as costs incurred with purchasing DC house technology and possible lack of government support in supplying the needed funding for installation.

II. Background

There are an estimated 1.4 Billion people in the world today that have no access to electricity [1]. Due to the need of creating conditions for economic growth, this figure represents a significant issue in today's world as electricity is essential for basic needs such as lighting, refrigeration, and the operation of most household appliances. Without these essential services, schools go unlit, some medicines cannot be stored, and water must often be hand-carried for miles just to supply adequate hydration and sanitation.

The DC house project provides a method to tackle the large issue of energy poverty in places where electrification has yet to be accomplished. Operating off several low-cost renewable sources, a DC house will provide basic energy needs to a single family while eliminating the need for transmission of grid power to certain remote places where transmission is not cost-effective for the parent country. Using DC sources will eliminate the need for costly, maintenance-heavy generators and their incurred non-monetary costs such as exhaust fume-related illness, burn injuries from ignited fuel, and noise pollution. In addition, low-cost LED lighting is becoming more prominent and cost effective, replacing the need for dangerous Kerosene lamps that still used in many remote villages.

With the requirement of being low on cost, the DC house will utilize a single DC bus voltage running from the source to several outlets installed throughout the house, much like modern North American systems use a standard 120VAC, 60Hz voltage for operation of all appliances and household items requiring energy. Due to the nature of devices needing different DC voltages for operation, the outlets will need to vary these output voltages to suit the appliance's input voltage requirement.

In this project, we will design the outlet by which power from the main DC bus will be supplied to devices. The design is described in the requirements section of this report.

III. Requirements

The purpose of the Variable Output DC outlet is to provide a source of power for individual loads inside the DC house. As this project will most likely be deployed in parts of the world where knowledge of voltage and current are minimal, ease of use is paramount to providing a safe and reliable source of power to devices.

The maximum output of the outlet will be less than 90W, as the largest load found to be eligible for the system required no more than 80W. The system will allow for an output of 5V, 12V, 19V, and 24V. These voltages were chosen based upon a thorough investigation on devices that require a DC input and average usage among consumer products.

Isolation will be attained by use of an isolated converter topology such as a Flyback, switching DC-DC converter design implementing output voltage control feedback loop with a non-isolated feedback loop. The need for isolation comes from the requirement of protection for the outlet/main bus interface, as without isolation, excess load could endanger the DC house and other devices connected throughout. The printed circuit board will be created in a PCB editor and sent to a professional PCB etching company to ensure a low-noise, highly-efficient operation. Most discrete components will be surface-mounted to increase efficiency and reduce size of the board such that the entire converter will fit into a 3-gang, plastic, old-work or new-work electrical box.

The plug going into the outlet requires a selector pin that will change the output voltage of the device depending on pin placement. The pin will complete the feedback circuit with resistors that adjust the duty cycle of the switching waveform controlled by the switching regulator IC. A power switch will be incorporated into the face of the outlet to provide a safety mechanism that allows the input to be completely disconnected when no load is present. The separation of the power contacts of the plug must have a separation that, at minimum, abides by the National Electric Code to prevent arcing and fire hazard [2].

IV. Design

There are three main components to the design of this project: the DC/DC converter, the plug/outlet interface, and the packaging of the printed circuit board with receptacle inside a standard electrical box. Much of the design section is focused on the Converter as the rest of the components were found and purchased. This was more cost effective and presented a viable solution which will be later outlined in Testing and Development

Figure 4-1 shows an overall block diagram describing the how the system operates with regard to the main bus input. The converter along with the feedback loop and selector resistor mounted inside the plug will select the correct output, and will supply power to the DC load.

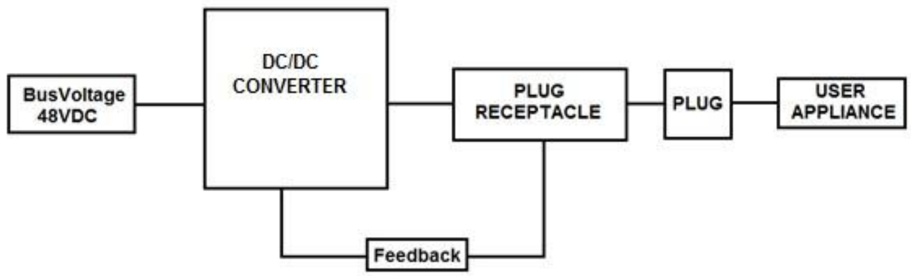


Figure 4-1: Overall system block-diagram

The Flyback DC/DC converter design was primarily based around Linear Technology's LTC3803 Constant Frequency Current Mode Flyback DC/DC Controller for reasons that will be detailed in the design section. Both the plug and receptacle were designed using pre-existing available parts, easily available online or in various hardware stores.

The user appliances will be examples based on research into modern DC applications and completely dependent on the end user.

A. Converter Design

Topologies Considered

1. Non- Isolated Buck Converter

Initially it was thought that for a simple step-down requirement, such as 48Vdc to 12Vdc, the simplest topology, such as the buck converter would satisfy the end user functionality requirements needed for operation of the outlet. However, upon further discussion of the nature of the outlet and its primary users possibly not understanding the DC voltage requirement, it was determined isolation was needed to protect the internal circuitry and rest of the DC house from overloading on the user-end. Isolation is necessary for this converter to provide some level of protection to the house's system bus and prevent damage to other converters and possibly any batteries present in the system.

2. Non-Isolated Buck/Boost Converter

For the same reasons that the Buck converter was decided against, the buck-boost was determined to be unable to meet requirements due to lack of isolation.

3. Isolated Forward Converter

The Forward converter was the first of the isolated, switched-mode converters to be considered and is considered to have better input and output characteristics than a Flyback converter, which reduces the necessary filtering on the input and output to reduce current and voltage ripple respectively. However, the design requires more components, namely an additional inductor, increasing the cost and size of the design. Considering this project should be suitable for low cost deployment with the DC house, as well as minimal available space, a smaller number of components were deemed more ideal.

4. Isolated Flyback Converter

According to [3], the Flyback converter, as seen in Figure 4-2 is mostly used in applications under 100W. Because the outlet will be supplying less than 90W, the Flyback converter meets this specification. Also, due to its simpler design and lower part count, a Flyback converter is better suited than a Forward converter in addition to being able to provide necessary isolation from the system bus. The negative aspects in using a Flyback converter include required extra filtering on the input and output to provide stable voltage output and to limit current input pulses, the possibility of voltage spiking across the switch due to transformer leakage inductance, and limitations from commercially available transformers. The added filter requirement is relatively minimal compared to the added cost of additional circuit components and space on the PCB.

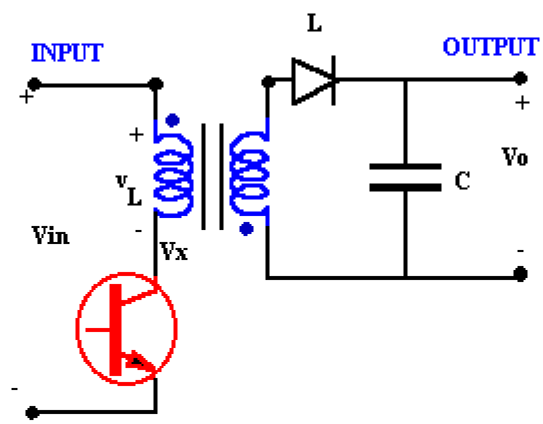


Figure 4-2: General Topology of a Flyback DC/DC Converter

Overall DC/DC Converter Design Process

Input Voltage

The wide input voltage requirement stems from the lack of a set system bus voltage level, for testing and design purposes 48V was chosen as the input voltage. However, if the system bus voltage differed either up or down, it was preferred that the system be able to accommodate this change.

Output Voltage and Loading

With the unique nature of this project, building a DC/DC converter that has a wide output range presents a distinctive challenge. Most converters are designed to operate at only a single output voltage, whereas this converter will need to maintain four independent voltages and preserve all the characteristics of a functional converter.

Calculations

Once a converter topology was decided, designing the circuit started with calculating voltage and current ratings of components to determine the approximate sizes and ratings. These calculations can be found in Appendix A with results in Table 4-1. The Python Mathematics software was used to rapidly calculate all known variables quickly in order to expedite new quantity inputs each time a change was made to the design; this code can be seen in Appendix B.

Like most circuit designs, calculations are the primary way to gain insight into the behavior of a circuit before construction. In physical design, however, calculations fail to predict some of the errant behaviors and non-linearities that are almost guaranteed to occur. This is the primary reason LTSpice became the prominent design tool used in this project, as Flyback converters are known for several anomalies that can happen during design. The following equations along with Appendix A show the calculations used in the initial phase of design, however many adjustments were made as the project progressed and documenting all of them would exceed the reader's interest.

Feedback Resistor Divider

$$R_2 = \frac{V_{out} - 0.8V}{0.8V} * R_1 \qquad (4\text{-}1)$$

R_1 was selected based on minimization of current through the feedback loop. This is not taking into account feedback opto-isolation, which has its own set of biasing calculations dictated by opto-isolator datasheets.

Transformer Turns Ratio

$$\text{Turns ratio} = \frac{N_p}{N_s} = \sqrt{\frac{L_P}{L_S}} \qquad (4\text{-}2)$$

where L_P= Primary Inductance and L_S= Secondary Inductance

As stated later in the report, turns-ratio was based on available transformers from various suppliers and calculations were based on transformers that had suitable frequency and power ratings.

Table 4-1: Calculations performed to determine appropriate component sizing. See Appendix A for equations.

	Vout (V)	Dmin (%)	Dmax (%)	Ip-average (A)	Co (µF)	ESR (mohm)
CCM	5.000	15.02%	20.95%	0.919	71.623	0.044
	12.000	28.26%	37.15%	1.155	224.944	24.770
	19.000	37.93%	47.84%	1.392	372.927	19.243
	24.000	43.39%	53.50%	1.562	466.156	17.215
DCM	5.000	13.64%	19.02%	0.192	125.083	17.215
	12.000	25.63%	33.66%	0.429	278.857	17.215
	19.000	34.37%	43.31%	0.665	432.812	17.215
	24.000	39.30%	48.40%	0.834	542.889	17.215

As indicated by Table 4-1, there are two modes of operation for which values were calculated, continuous conduction mode (CCM), and discontinuous conduction mode (DCM). As evident from research into Flyback converters seen in Linear's Application Note 19 [8], the ideal mode for higher efficiency and lower output ripple is DCM and was implemented into this design. Therefore, for the rest of this report, the converter should be assumed to be operating in DCM.

Switching Controller

The circuit controller requirements were straightforward in that a controller was needed for external switch control as well as a wide input voltage range. The need for an external switch was due to the larger current capacity rating needed to produce 90W on the output. Unable to find any controllers from Linear Technology with integrated switches that could handle the amperage needed for each full load at different output voltages, several controllers with external switch control were investigated using simulations.

B. Simulations

For most of the design, Linear Technologies' LTSpice was used for simulations to simplify the transition between design and testing. LTSpice has all of the components offered by Linear Technologies modeled in the software libraries, which reduces time spent on modeling and increases time available to design and test. Using Linear Technologies website [3], several Flyback controllers were found that fulfilled the requirements as can be seen in the following set of simulations.

The progression of simulations followed research into which controllers and components would function the best for such a unique converter design, starting with the LT3805 Adjustable Frequency Current Mode Flyback controller with Opto-isolator in the feedback loop. Each simulation was run multiple times to determine if a stable output could be realized. If the simulation would not return results, further research was performed to improve the design.

For simple reference, each subsequent design is referred to by version number for ease of reference. In addition, all designs were simulated using 48VDC input and an initial load of 1A. If an output was realized in terms of a steady-state voltage signal, further testing was commenced. The following sections will provide an example of each design progression with plots of input, output, primary inductor current and switching signal. The transient plots shown represent the signal probed at steady state, so time intervals on the x-axis will vary.

Version 1.0

In the first concept design, the LTC3805-5 Flyback controller was selected due to its controllable switching frequency (which aids transformer choice later in the design). The circuit design seen in Figure 4-3 primarily derives from the circuits seen in the application notes in the LTC3805-5 datasheet [4]. An opto-isolator was implemented into the feedback loop to provide more isolation from the controller to the output; this proved to be difficult when varying output voltages from same controller.

The four resistors seen connected to the output represent the four selected values based on the resistor divider that calculate the needed feedback input.

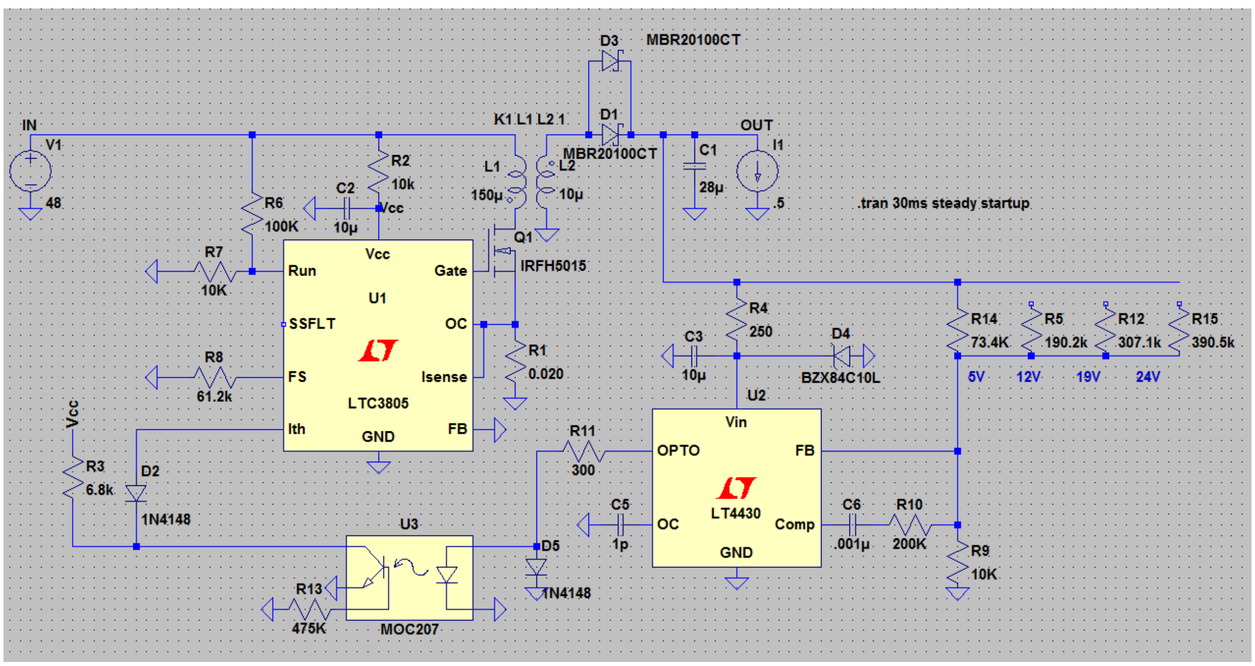


Figure 4-3: Version 1.0, Isolated Flyback converter using LTC 3805 Flyback controller, feedback isolation and LT4430 for opto-isolator control.

Version 1.0 was simulated initially with 48Vdc input, and a load of 1A on a 12V output voltage. As seen from the simulation figure, the converter failed to maintain any voltage output level, likely due to the instability of the feedback caused by the opto-isolation circuit.

Further simulations with different feedback resistors selected failed to produce results as well; consequently no further investigation was done with this topology.

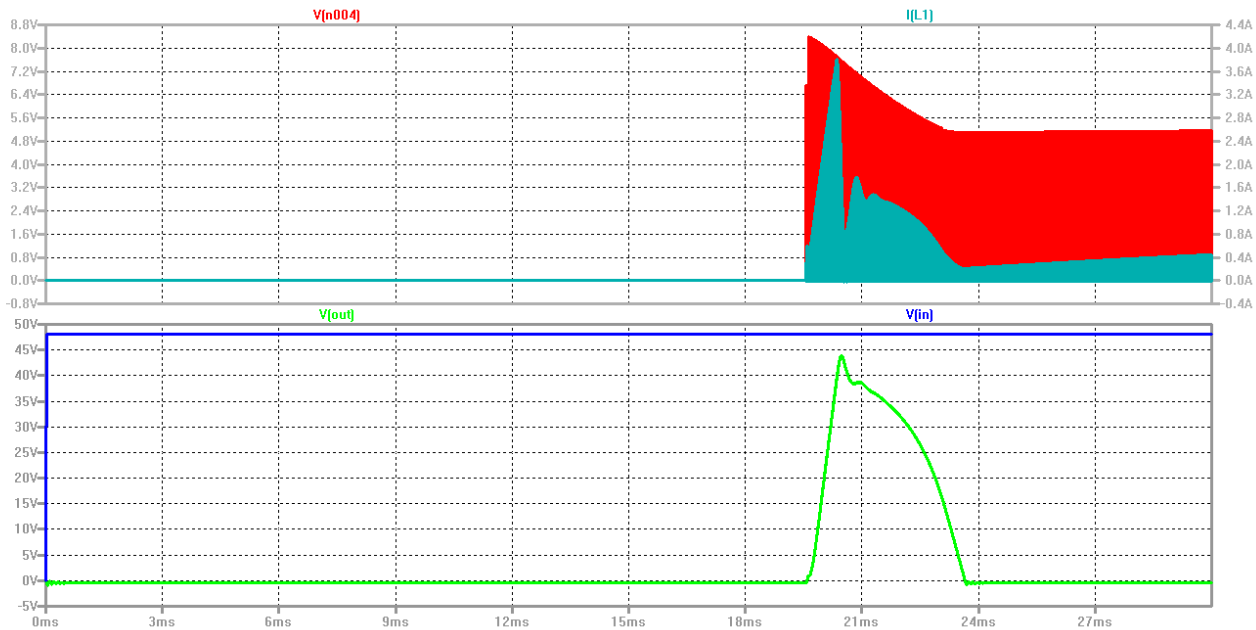


Figure 4-4: Version 1.0 simulation results. Top Plot: MOSFET Gate voltage (red) and Primary inductor current (blue). Bottom Plot: Input voltage (blue) and output voltage (green).

Version 1.1

To make the design process simpler the main controller was changed from the LTC3805 to a LTC3803, which reduced the number of pins on the chip from 10 to 6, thus subsequently easing PCB design. The LTC3803 has a set frequency of 200 kHz, controlled by an internal oscillator [7]. According to the datasheet, constant frequency is maintained down to very light loads, which is beneficial for some of the lighter loads utilized with the outlet.

In addition, research on existing transformers from chosen vendor CoilCraft [6] showed that many of Coilcraft's products are designed for 200kHz or 250kHz, which reinforced the use of the LT3803. Again, the feedback loop was implemented with opto-isolation using the LT4430 Opto-driver.

In addition to the change in controller, a voltage regulator sub-circuit was added to maintain a controlled voltage for the LT4430 opto-coupler driver, as can be seen with the rest of the circuit in Figure 4-5.

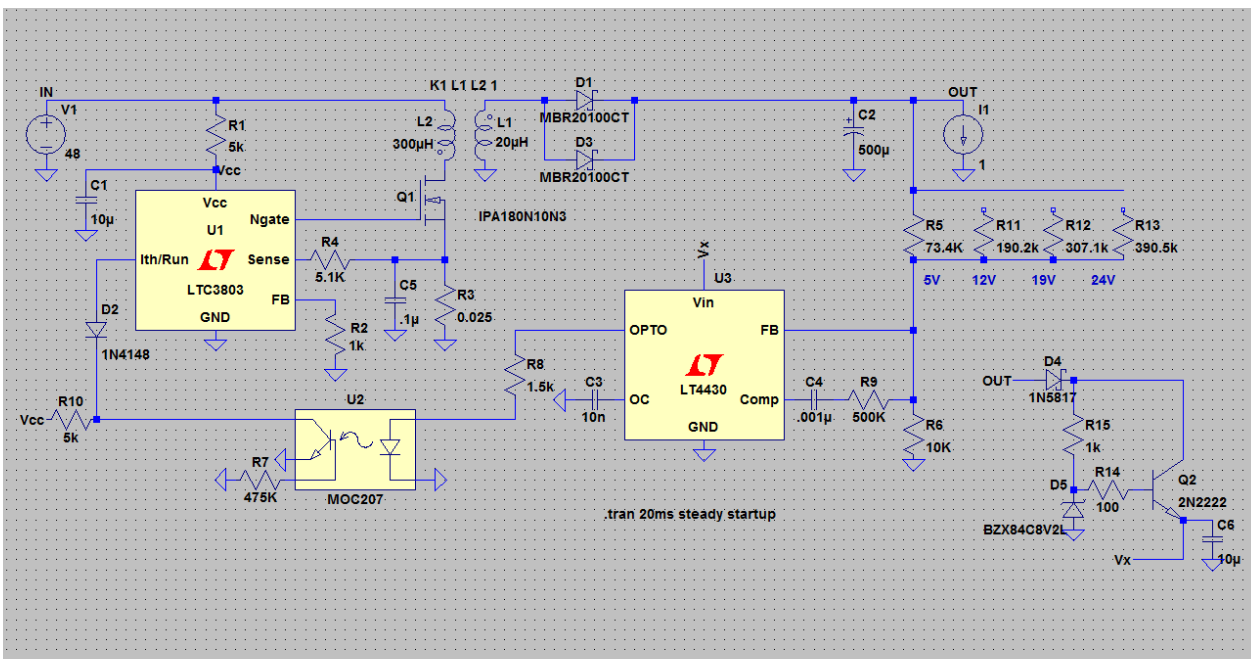


Figure 4-5: Isolated Flyback converter using LTC 3803 Flyback controller, feedback isolation and LT4430 for opto-isolator control.

Version 1.1 could be tailored to a specific output voltage as long as the component values changed each time the feedback resistor changed; this was not an option for meeting requirements of one converter design. The difficulty was discovered again while using opto-isolation, which affected stability in the feedback loop, causing inaccurate pulse width modulation inside the switching regulator.

The simulation was run once again with a 48Vdc input and 1A load on 12V output voltage, and as seen in Figure 4-6, and shows a moderately stable output and inductor current.

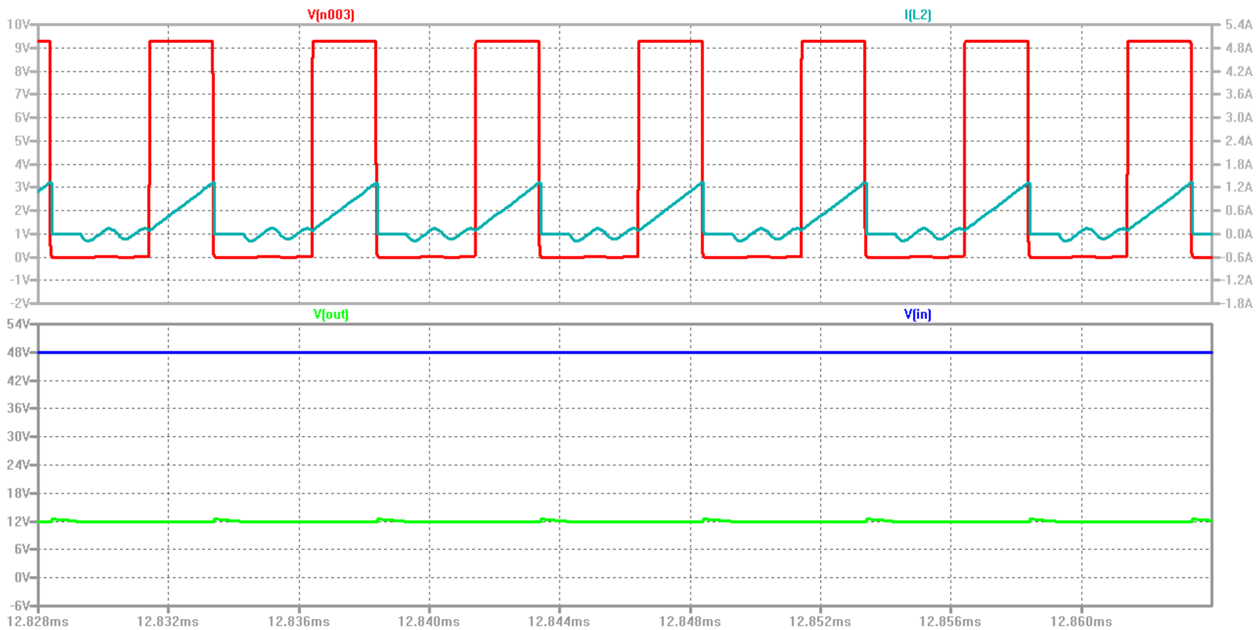


Figure 4-6: Version 1.1 simulation results. Top Plot: MOSFET Gate voltage (red) and Primary inductor current (blue). Bottom Plot: Input voltage (blue) and output voltage (green).

Regardless of these seemingly positive initial results, when load regulation testing was performed with output voltage at 5V and load set to 3A, the voltage ripple on the output increased to 42%. The results can be seen in Figure 7 with the large amount of ripple on the output voltage. This was unacceptable, thus more research was needed to improve the design of the converter.

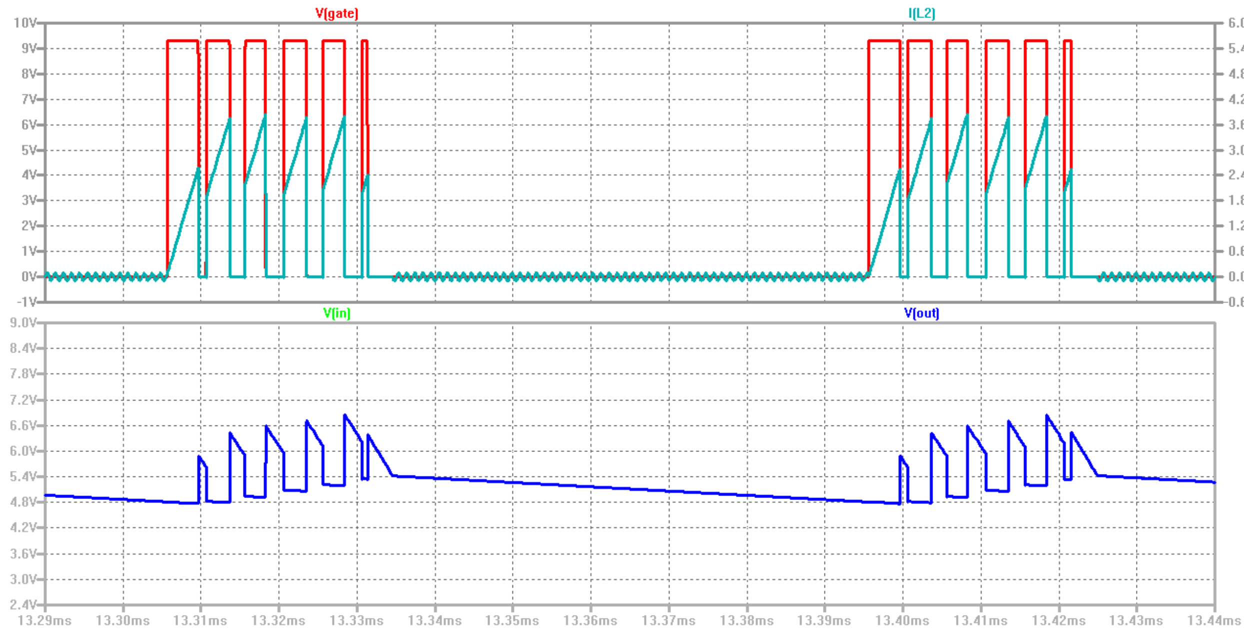


Figure 4-7: Version 1.1 simulation results with 48Vin, 5Vout, and load of 1A. Top Plot: MOSFET Gate voltage (red) and Primary inductor current (blue). Bottom Plot: Input voltage (blue) and output voltage (green).

Version 1.2

This version as seen in Figure 4-8 was simulated to eliminate possible error causing variables and verify the basic circuit operation with optical isolator removed. This is the design provided by the test fixture of the LT3803 that comes pre-installed in LTSPICE. This was a successful circuit and proved to be the basis for the final circuit design

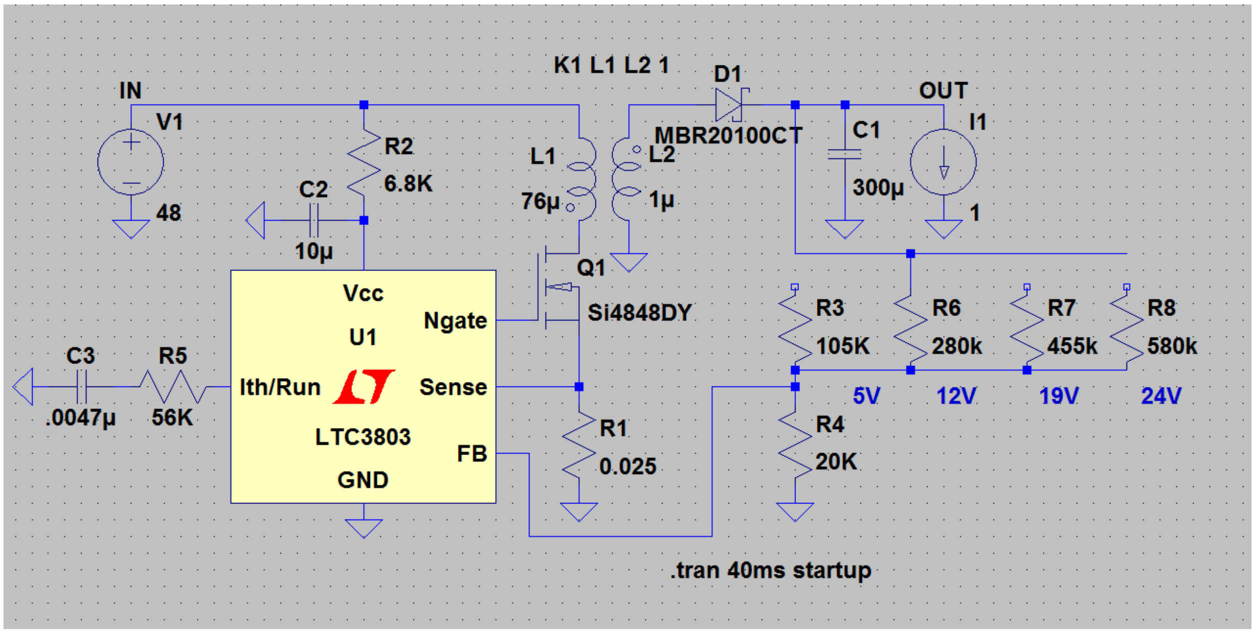


Figure 4-8: Version 1.2; Flyback converter using LT3803 with non-isolated feedback using test fixture in LTSPICE.

The only change made to the fixture was the addition of the four feedback selection resistors that made simulation testing easier. The simulation showed promising results for all four output voltages and various loads.

The stipulation to this design is the transformer, which would require custom winding by a professional. At this point, a professional winding would have exceeded the maximum budget allowed due to the manufacturer's demand of ordering production-sized quantities. However, as seen in Figure 4-9, the results were optimistic at 12Vout. Other simulations were performed at all for output voltages and various loads, all showing positive results with high efficiency and minimal output ripple.

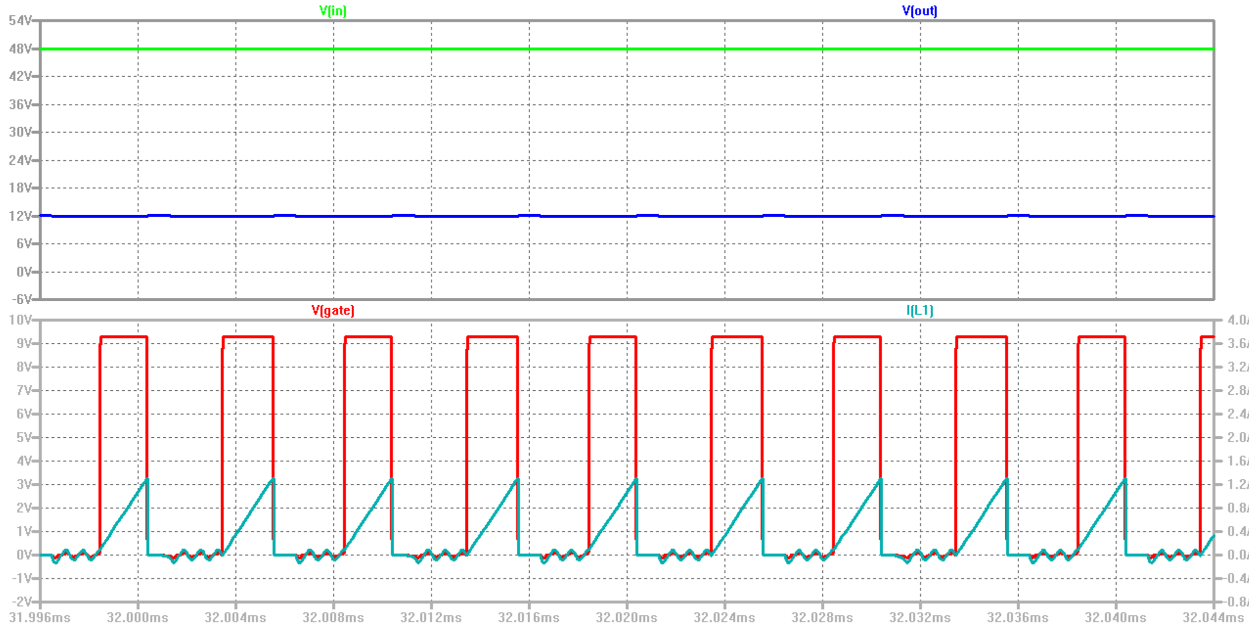


Figure 4-9: Version 1.2 simulation results with 48Vin, 12Vout, and load of 1A. Top Plot: Input voltage (green) and output voltage (blue). Bottom Plot: MOSFET Gate voltage (red) and Primary inductor current (blue).

A further issue with version 1.2 was the lack of isolation on the feedback loop. As each design progressed, it was noted that the feedback isolation was a variable that was continually causing functionality issues to occur. At this point, it was proposed that proceeding with a non-isolated feedback loop could be a solution. This meant compromising one of the requirements of the project, however after further discussion, it was deemed necessary to achieve at least partial functionality, even if that meant eliminating the feedback isolation altogether. However, persistence was necessary at minimum to discover if isolation was achievable with each new design.

Version 1.3

In this version, the same test fixture was used; however, the isolated feedback was implemented again to verify whether isolation was still feasible with the simplified design. The opto-driver was removed and replaced with a more simplified opto-coupler design. As seen in Figure 4-10, V_{bias} is connected directly to the collector of the photo-transistor inside the opto-coupler, offering a direct biasing voltage, eliminating the need for the driver circuit.

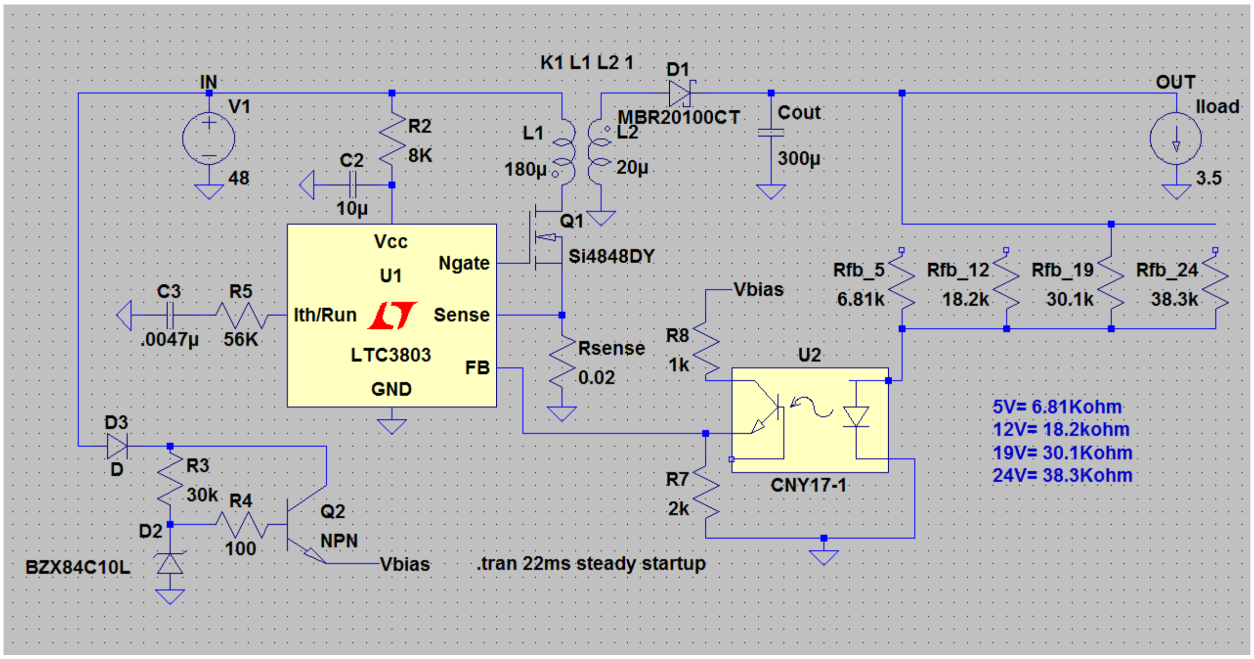


Figure 4-10: Version 1.3; Isolated Flyback converter using LT3803 test fixture in LTSPICE in addition to voltage regulator used to provide stable bias voltage to opto-coupler.

Version 1.3 was largely a promising circuit, with completely redesigned feedback circuit as mentioned earlier. Figure 4-11 shows simulation results that give moderate ripple at the 12V, 1A output. Aside from the split duty cycle, more simulations seemed to show that this could be a working converter.

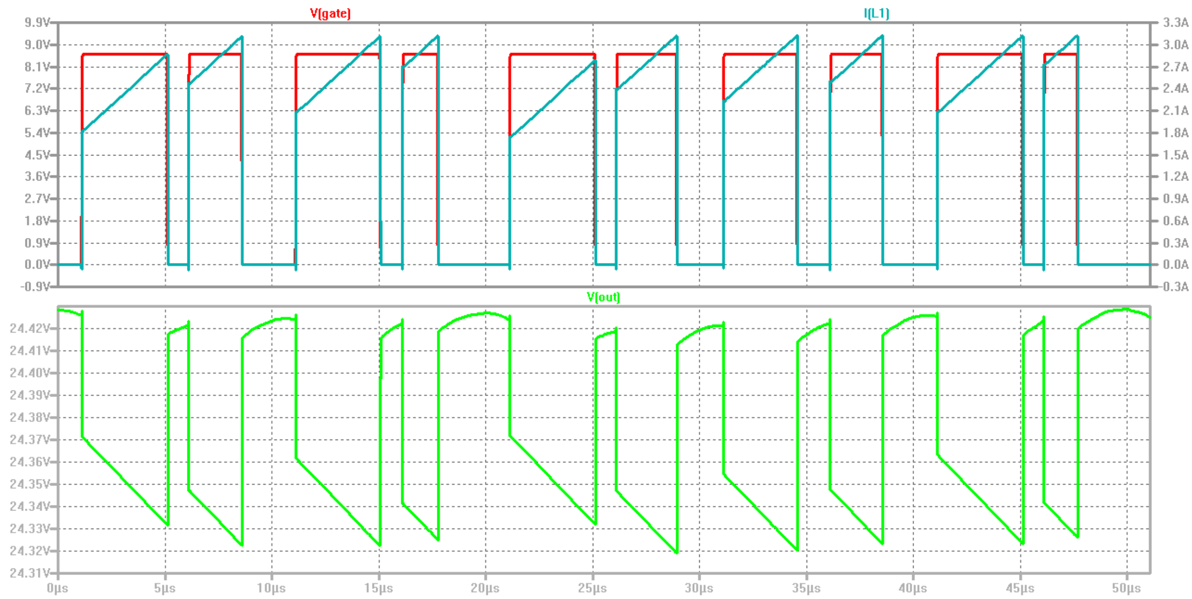


Figure 4-11: Version 1.3 simulation results with 48Vin, 24Vout, and load of 1A. Bottom Plot: Output voltage (green). Top Plot: MOSFET Gate voltage (red) and Primary inductor current (blue).

The reason this circuit wasn't pursued into development once again stemmed from the fact that custom winding an inductor with a required power rating above 90W is largely unattainable with the size requirements of the converter. Broad searches and consultations proved that finding any transformer over 30W for small Flyback converters was unrealizable.

In addition, upon consulting with Greg Hollister, an Electrical Engineer who specializes in Flyback circuits, it was pointed out that opto-couplers come in various current ratio settings. This meant that for each output voltage, there would be a different current flowing through the feedback circuit, leading to the need for an all-encompassing opto-coupler, which unfortunately does not exist.

Version 1.4

This version of the Flyback seen in Figure 4-12 was influenced by the available transformers from Coilcraft. The largest Flyback transformer was capable of handling 30W, thus to provide the required power three transformers were placed in parallel along with three MOSFET's. Additional alterations were made to minimize power losses in the circuit, such as raising resistor values to reduce current and biasing the V_{in} to the LT3803 to be as close as possible to its internally regulated voltage. The bias voltage was achieved by way of the voltage pre-regulator found in the LT3803 Datasheet (names were changed to reflect components in Figure 4-12:

> "An external series pre-regulator consisting of series pass transistor Q4, Zener diode D4, and bias resistor R3 brings VCC to at least 7.6V nominal, well above the maximum rated VCC turn-off threshold. Resistor R4 momentarily charges the VCC node up to the VCC turn-on threshold, enabling the LTC3803." [7]

In addition to the previously mentioned changes, three more output capacitors were added in order to reduce the amount of equivalent series resistance (ESR), which has been shown to reduce the output voltage ripple.

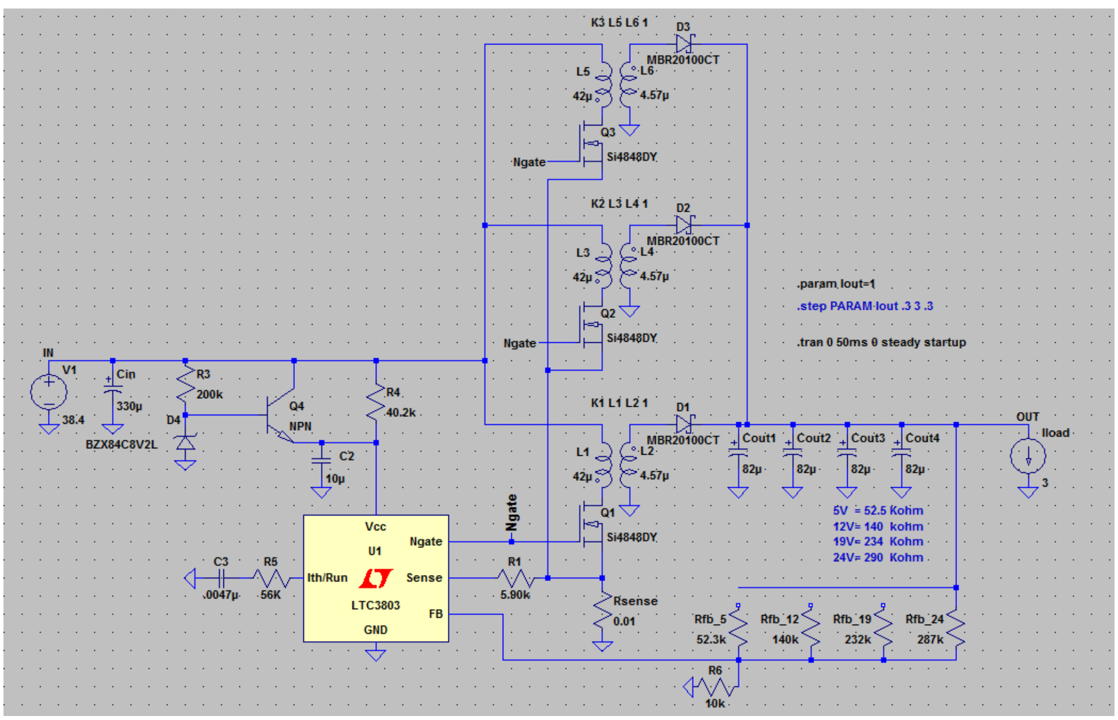


Figure 4-12: Version 1.4; isolated Flyback converter using LT3803 controller, added pre-regulator, split MOSFET/Transformer configuration and multiple output capacitors to reduce equivalent series resistance (ESR).

Figure 4-13 shows the simulation of version 1.4 and encouraging results at an output voltage of 12V with less than 1% voltage ripple at a load of 1A. Further testing was completed with loads from 0 to 100% max (3.5A), as well as varying input voltage ±10% and can be seen in Appendix C.

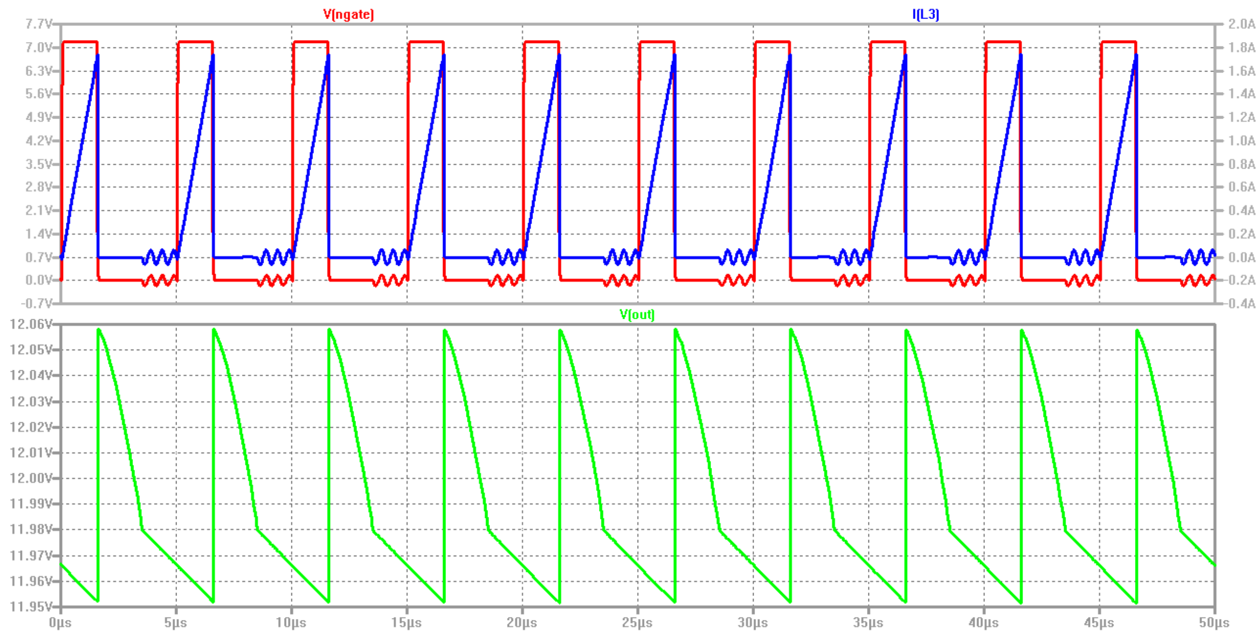


Figure 4-13: Version 1.4 simulation results with 48Vin, 12Vout, and load of 1A. Bottom Plot: Output voltage (green). Top Plot: MOSFET Gate voltage (red) and Primary inductor current (blue).

Inevitably, it was version 1.4 that was settled upon as the converter that would be used in the development of the outlet. With stable outputs, and superior line and load regulation, it was determined that this converter, once installed on a Printed Circuit Board would function adequately to meet the requirements of the project.

V. Development and Testing

Plug

The plug is one of the main design concerns in the wall outlet development, considering it is the user interface of the outlet, and is the key component in how the multi-variable output will function

For the initial design, it was speculated that five pins were needed, two of which would carry power and three others that provide information to the plug. An example of the concept design of the first plug can be seen in Figure 5-1. One pin was to be used for a feedback loop to set the proper output voltage. The last two would be used to provide a turn on/off function for the switch to limit power loss and excessive output voltage without the feedback resistor connected. The turn-off function is a concern due to the nature of Flyback controller feedback; without a closed loop with a resistor, the duty cycle of switching will try and compensate by rising indefinitely, causing a large voltage spike on the output. This will eventually lead to component damage and possible user danger.

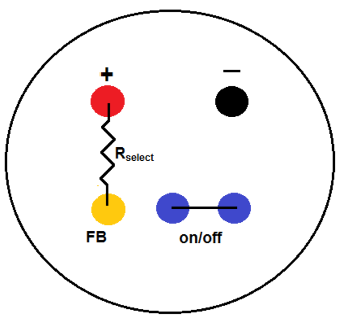


Figure 5-1: Concept Design of plug face

Consequently, an existing plug design available commercially was preferred in order to lower costs and eliminate the need for designing a plug from scratch. It was decided that a three prong plug with a non standard orientation in the United States would eliminate possible dangers of plugging in AC appliances to the outlet. The plug used was found available from McMaster-Carr [8] and can be seen in Figure 5-2 with specifications listed in Table 5-1. The three prong plug eliminates the safety feature of automatic outlet power off, however to compensate for this exclusion a switch was added between the main bus and the input to the circuit.

The key to this plug design is that the feedback resistor can be soldered inside the plug, along with appropriately sized wires that will accommodate each load. Once the plug is closed, it will be decided by the user or further project redesign to decide how the appliance is attached, as this goes beyond the scope of this project.

Figure 5-2: a) open view of plug; b) closed view of plug.

Table 5-1: Manufacturer Specifications of Plug

Connection	Quick-Wire Male Plug
Number of Blades/Prongs	3
Connection Type	Plug
Plug Type	Quick-Wire Male Plug
Connection Style	Straight-Blade
Grade	Commercial
Special Feature	General Purpose
Blade Material	Brass
Housing Material	Plastic
Plastic Type	Nylon
UL Specification	UL Listed

Outlet

The outlet used was selected to match the plug as well as provide a durable device that would take continual usage of long periods of time. The outlet was found from the same company and can be seen in Figure 5-3 with specifications listed in Table 5-2. The contacts on the rear of the plug are easily accessible and will be wired to the board via 14AWG insulated copper wire.

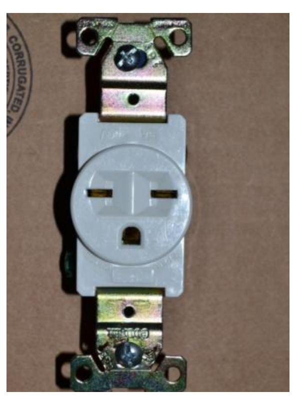


Figure 5-3: McMaster-Carr, straight-blade receptacle.

Table 5-2: Manufacturer specifications of receptacle.

Receptacle Type	Single Receptacle
Single Receptacle Style	Standard
NEMA Style Number	6-30 (Straight-Blade)
Number of Blades/Prongs	3
Connection Type	Receptacle
Connection Style	Straight-Blade
Three-Blade Straight-Blade Style	6-30 (With Ground)
Voltage (VAC)	250
Current (Amps)	30
Special Feature	General Purpose
Contact Material	Copper Alloy
Housing Material	Plastic
Color	Black
Specifications Met	Canadian Standards Association (CSA) and Underwriters Laboratories (UL)
CSA Specification	CSA Certified
UL Specification	UL Listed

Overall Electrical Box Design

In designing the box that would house the converter and make it a useable outlet, it was determined early-on that an existing standard should be used to ease installation and provide a stable housing structure for the internal circuitry. Additionally, with the use of a semi-standard outlet, the mounting holes already align making assembly much easier and eliminating the need for another design step. For this, a standard 3-gang, new-work electrical box was chosen as it best fits the size of PCB used for the converter. Inevitably, a smaller 2-gang box would work if the size of the board is reduced, which at this point is unachievable.

The box is ideal in that it is already widely used in the construction industry, is highly-durable, and provides a level of customization needed for this project. Figure 5-4 is an example of the same box used for mounting and housing the circuit board, receptacle, and safety switch.

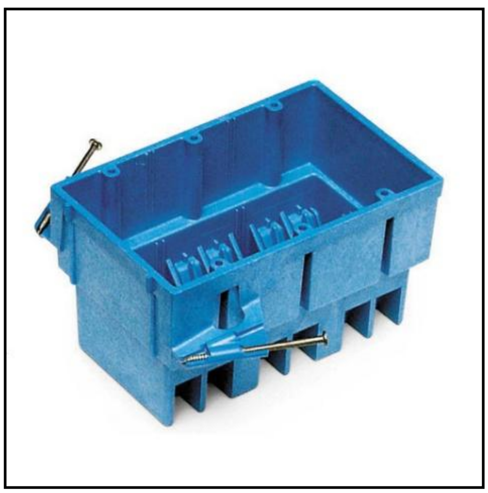


Figure 5-4: 3-gang, new-work, electrical box

Breadboard Prototype

For most circuit designs the next step would be to build and test using a breadboard, as this provides a low-cost, simple way to prototype a circuit without going through the process of PCB layout only to have the hardware malfunction once installed. However, a breadboard has limitations due to its inherent excess resistance, capacitance, and inductance. A Flyback converter with a switching frequency of 200kHz provides many opportunities for noise to be introduced into the feedback loop, thus rendering the circuit inoperable.

Nonetheless, the design of the Flyback version 1.4 was implemented with a breadboard. Figure 5-5 shows the breadboard construction. One can notice from the picture the many wire loops created, allowing for multiple opportunities for noise generation. Details of the results are provided in the testing section of this report.

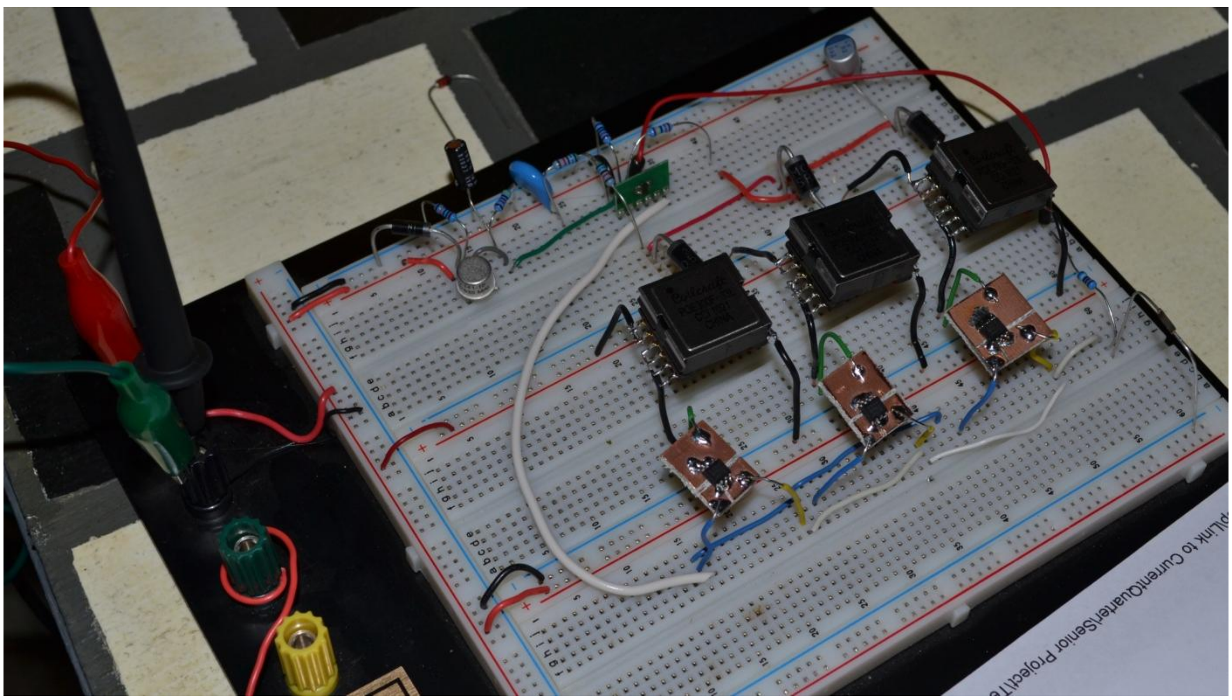


Figure 5-5: Breadboard prototype of Version 1.4

Also seen attached to the breadboard are surface mount components soldered to breakout boards. This again introduces more resistance, capacitance, and inductance into the circuit, affecting operation of the converter. However, these parts were the exact components to be used in the final design so their use on the breadboard was essential and unavoidable.

Printed Circuit Board

Using the final working version 1.4 from the simulation, a Printed Circuit Board (PCB) was created using ExpressPCB. This software provides a simple user interface for limited production of PCB's without the need for etching equipment or chemicals.

Express PCB can utilize a netlist from any spice program to make connecting traces much simpler. Using LTSpice, the netlist was exported from the final circuit design into ExpressPCB. The ordered component specifications were then used to generate pad layouts and connect pads via traces. The design based off version 1.4 can be seen in Figure 5-6.

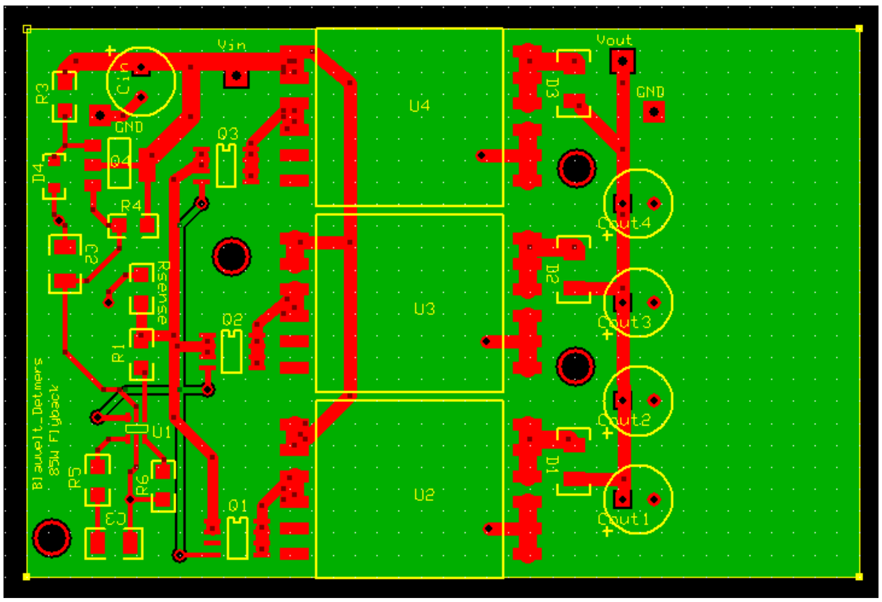


Figure 5-6: Version 1.4 layout in ExpressPCB.

During design of the PCB various traces widths necessary for proper operation were taken into consideration. 0.080" width was used for all power-carrying traces and 0.025" to 0.050" width for other traces depending on the available space on the board. A ground plane on the reverse side is necessary to help reduce noise in the circuit and maintain a stable feedback loop. All trace lengths were kept to a minimum to reduce resistive loss, capacitive coupling, as well as additional noise.

TESTING

A majority of the testing focused on converter functionality, as the plug and outlet only required continuity testing to verify the connections were acceptable.

Breadboard

As read in the design section, prototyping with bread boards for power supplies can be arduous work. Due to the high impedances seen in breadboards, any circuits operating with frequencies in the kilohertz range tend to malfunction from excess electromagnetic interference (EMI) and the additional resistance, inductance, and capacitance between contacts.

Nevertheless, a breadboard prototype was constructed to find out if the converter would function at all. Seen in Figure 5-7 is a picture of the test bench setup utilizing two power supplies in series supplying 40VDC (power supply digital display shows a "1." when at max of 20V), current-limited at 2A. Testing using precision lab equipment was deemed unnecessary for basic functionality testing.

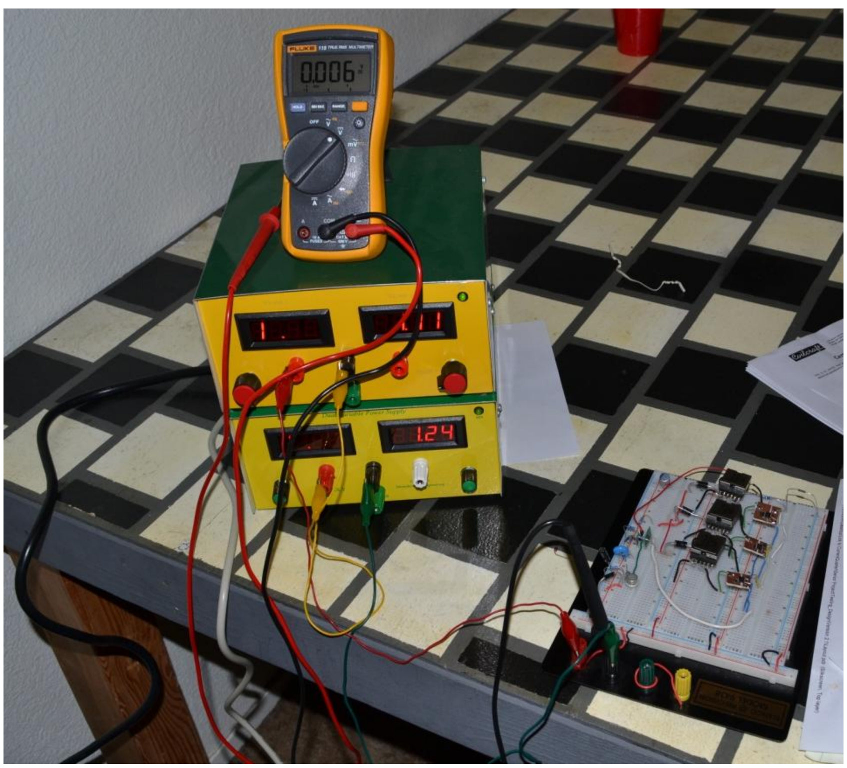


Figure 5-7: Breadboard prototype functionality testing setup using dual power supplies in series, supplying 40Vdc.

The test results can be seen in Table 5-3, however it is evident that the converter did not produce an output voltage for any of the feedback resistor values. The breadboard was re-configured to decrease distance between switching signal contacts from the LT3803 to the gates of the MOSFETs, however this redesign failed basic functionality tests as well.

Table 5-3: Breadboard test results

Vin (V)	Vout (V)
5	0.01
12	0
19	0.02
24	0.01

Since no realizable voltage output was generated from this method, it was thought that time and resources would be better spent on designing the PCB for fabrication.

Printed Circuit Board

Once the etched board arrived from ExpressPCB, all components were soldered, and testing commenced on the converter itself.

Calculations seen in appendix A and simulation results dictated the values and ratings of component that were soldered on the PCB. Shown in Figure 5-8 is the actual PCB with all components in place and leads for testing soldered to appropriate pads.

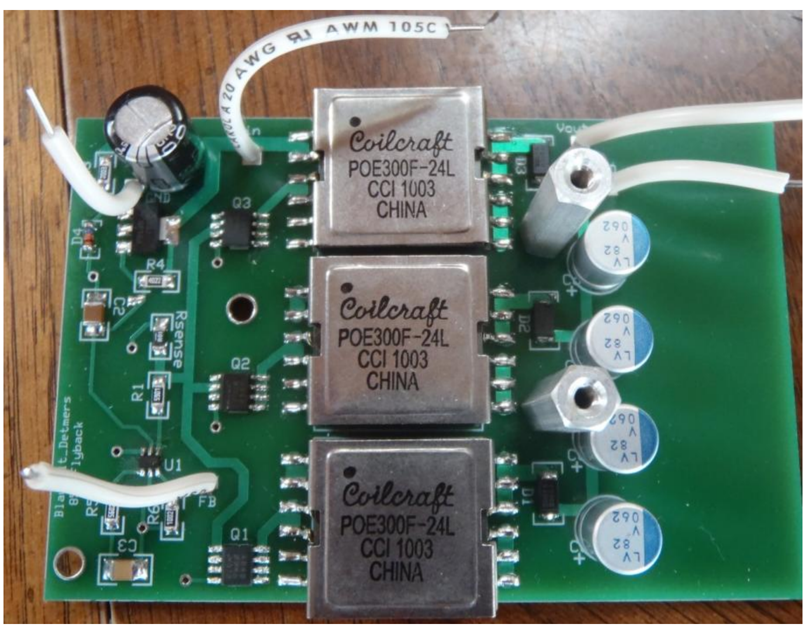


Figure 5-8: Printed circuit board of version 1.4 with components and testing leads soldered in place.

Version 1.4 Testing Results

The first qualitative tests of the PCB showed optimistic results, as all four output voltages were realized upon feedback resistor replacement. Figure 5-9 shows a plot of the 5V output voltage waveform and only a small amount of ripple is observed.

Figure 5-9: Results of 5V output voltage ripple during PCB testing

However, as small amounts of load were applied, the MOSFETs began dissipating significant heat, and in some cases, were completely destroyed.

A different feedback resistor was inserted to bring the output to 12V, however similar results were viewed each test. By probing different points on the board, it was discovered that the voltage at the drain of the MOSFET's was showing signs of spiking and resonant oscillations.. Seen in Figure 5-10, these anomalies were characteristic of the leakage inductance incurred on the primary side of the transformers. In addition, the switch was showing signs of not turning complete off with each cycle, which could cause undue heating.

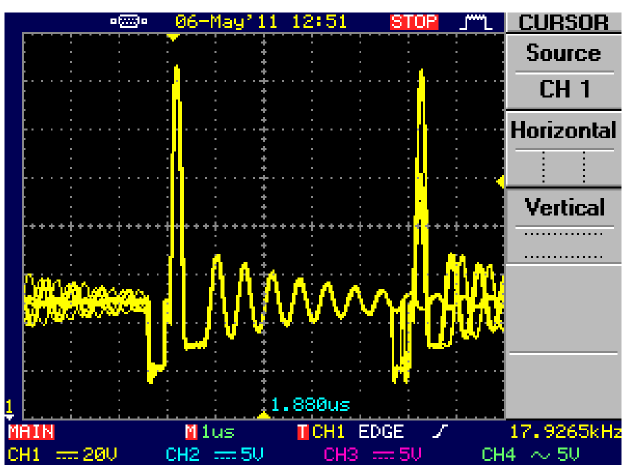


Figure 5-10: Voltage seen at MOSFET Drain showing
spike and resonant oscillations after turn-on cycle. (12V output)

In addition to the drain voltage, the gate node was probed to view the switching signal used to turn on the MOSFETs. Figure 5-11 shows the required 10V is achieved, however only a 6% duty cycle with slight noise after turn off was not optimistic.

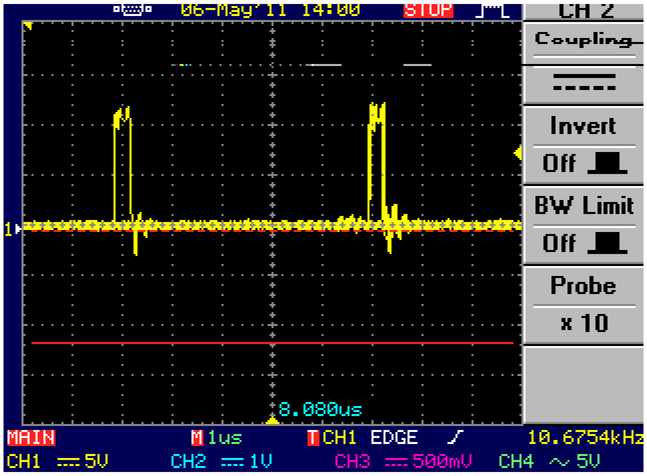


Figure 5-11: Gate Voltage at LT3803 Ngate (pin 6) or MOSFET gate.

Results from the first series of tests indicated that further design work needed to be considered. This was mainly due to the MOSFET overheating, voltage spikes seen on drains of the switches at turn-on, and oscillations occuring after switching on MOSFET drains.

VI. Further Testing and Results

The first remediation step was taken to adequetly drive the MOSFET gate signal, which was solved by adding an IC driver, more than capable of driving all three MOSFETs. The driver was useful in boosting the gate drive signal in order to supply the three switches with adequate voltage and current for turn-on.

The additional problems in testing the PCB were large drain to source voltage spikes across the MOSFET, which was rated at 150V. The spikes led to heating in the MOSFET and ultimately their destruction. Figure 6-1 below shows the voltage and current characteristics of a near ideal MOSFET in Flyback converter.

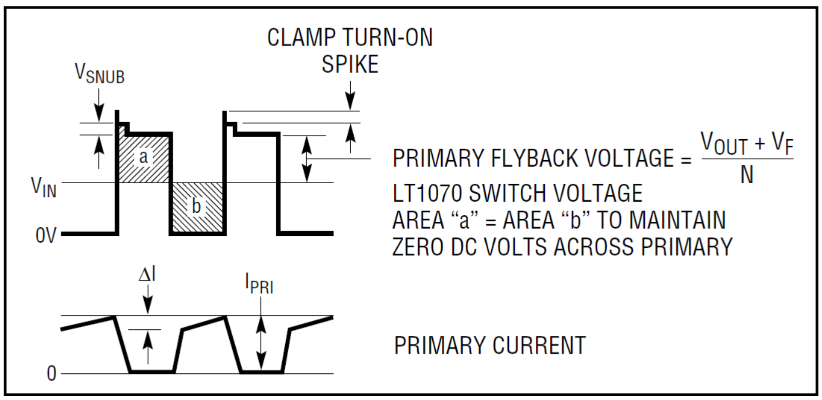


Figure 6-1: Ideal MOSFET voltage and current waveforms [8]

Flyback converters are prone to large voltage spikes from transformer leakage inductance during switching, particularly turn off, which causes a large power dissipation in the MOSFET. During simulation, there was no noticable voltage spikes, so the issue was largely not taken into account until hardware testing.

New MOSFETs with drain to source voltage of 200V, and drain current rating of 4.5A were ordered which could withstand the large voltage spikes and power dissipation. Further testing was conducted with only one of the three transformer/MOSFET combinations to limit possible component failures, however similar results were still being seen with heating and component failure.

Snubber Design

Once the cause of MOSFET failure was determined, the most common solution found was to implement a snubber circuit. After research into the design and implementation of a snubber for a Flyback converter, two different snubbers were considered and designed [13],[14],[15].

The most common and simplest solution to damping the ringing on the FET drain is a Resistor-Capacitor (RC) snubber across the switch. "The resistor provides damping for th eLC resonance of the power circuit, and the series capacitor prevents the voltages at the power stage switching frequency from being applied across the resistor." [15] Referencing the snubber design equations, values for the resistor and capacitor were calculated.

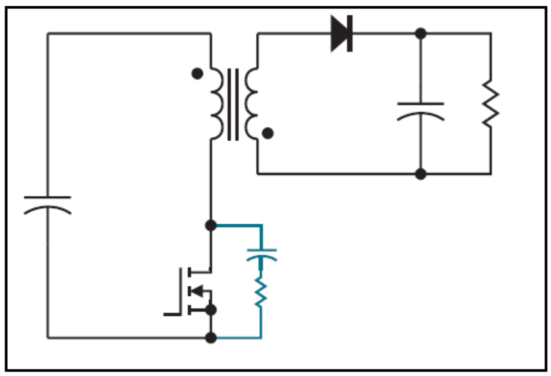


Figure 6-2: Flyback Converter with primary RC snubber (blue) [15]

With

$$L_{leak} = 0.430\mu H, \qquad f_r = 5MHz, and\ N = 0.56$$

where L_{leak} is the primary-side transformer leakage inductance taken from the Coilcraft specifications [6], f_r the frequency of the oscillation, and N the turns ratio of the transformer, the following calculations provided component values for an effective RC snubber:

$$Z = 2\pi f_f L_{leak} \tag{6-1}$$

$$R = Z = 2\pi(5MHz)(0.430\mu H) = 13.5\Omega \tag{6-2}$$

$$C = \frac{1}{2\pi f_f R} = \frac{1}{2\pi(5MHz)(13.5\Omega)} = 2.35nF \tag{6-3}$$

With R and C calculated, further verification of the design equations showed that the drain-to-source voltage and snubber power consumption would be as follows:

$$V_{DS} = V_{in} + \frac{(V_o + V_D)}{N} = 48V + \frac{24V + 1V}{0.56} = 92.64\ V \tag{6-4}$$

$$P = CV_{DS}{}^2 f_s = (2.35nF)(92.64V)^2(200kHz) = 4.04\ W \tag{6-5}$$

The second most common snubber consists of a resistor in parallel with a capacitor across the primary winding of the transformer, controlled by a diode, as seen in Figure 6-3a.

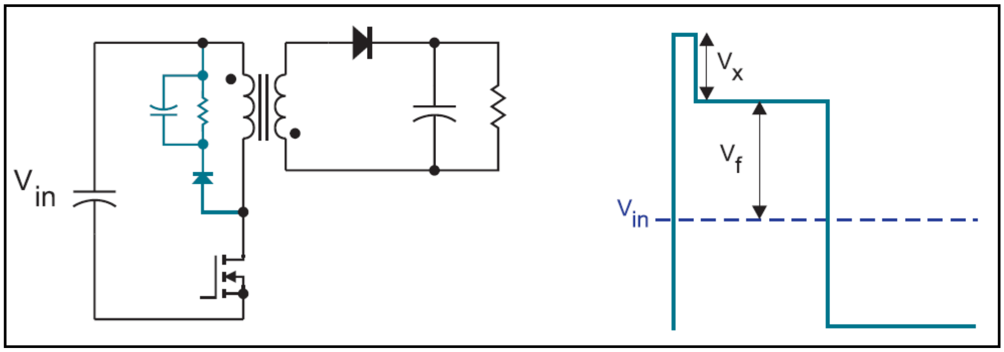


Figure 6-3: a)Flyback converter with RCD snubber (blue); b) Partial Waveform of Snubber Voltage decrease V_X

Based the previously mentioned article by Ridley, resistor and capacitor values for the RCD were calculated seen below. The resistor is crucial in this type of snubber as the capacitor only functions to maintain a constant voltage across the primaries. The voltage spike above the nominal V_{DS} of the MOSFET is V_X from Figure 6-3b, a typical value for V_X is ½V_f.

$$R = \frac{2v_x T_s(v_f + v_x{}^{max})}{LI_P{}^2} = 21.29\ k\Omega \tag{6-6}$$

The power in the snubber circuit must be higher than that of the power dissipated in the primary side of the transformer, and as seen below, this is satisfied.

$$P_l = \frac{1}{2}LI_p{}^2 f_s = \frac{1}{2}(0.430\mu H)(2.6)^2(200kHz) = 0.291W \tag{6-7}$$

$$P_{sn}{}^{max} = P_l\left(1 + \frac{v_f}{v_x{}^{max}}\right) = 0.872\ W \tag{6-8}$$

Further research into snubber design from Linear Technologies provided another option for implementing a voltage spike limiting circuit. A zener diode can be used in place of the resistor and capacitor in the RCD. This provides a more accurate and efficient design due to the voltage limiting ability of a zener diode.

Linear Technology has advice on this type of snubber and an example is seen in Figure 6-4. By using LT's design equations for [8], component sizes could be calculated for peak functionality.

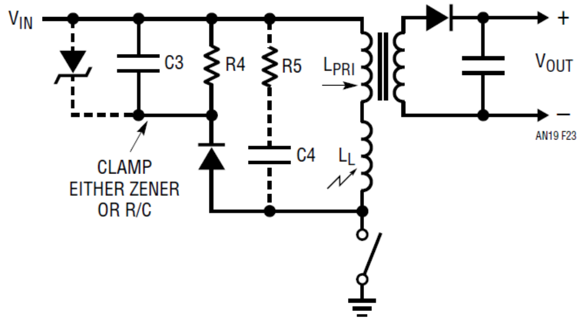


Figure 6-4: Linear Technologies Zener/RCD Flyback Snubber Circuit

For Linear Technologies calculations, V_m was used as the maximum voltage across the switch.

$$V_{ZENER} = V_M - V_{IN(MAX)} \tag{6-9}$$

However, to minimize voltage ripple and power dissipation the lowest possible zener voltage was chosen for the highest output voltage of this converter.

$$\frac{(V_o + V_D)}{N} = \frac{24+1}{0.56} = 44.64V \tag{6-10}$$

Inexorably, a 62V Zener was selected based on the minimum value from the equation with a margin of +15V for input voltage deviations. The power capability required for the zener was calculated to be:

$$P_{Zener} = \frac{V_Z I_{pri}{}^2 L_{leak}\, f_s}{2(V_Z - \frac{V_{OUT} - V_f}{N})} = 1.04\ W\ @\ 24V\ output \tag{6-11}$$

One of the potential downsides of this design is a possible higher cost for the zener diode, however after determining the zener voltage and power requirements this cost is minimal compared with the upsides.

Retesting

Before any new components were ordered or boards redesigned, tests were conducted to ensure that the new components and the designs would be an effective solution to the existing problems. The economic solution to these tests was a modification to the original PCB. The circuit design were implemented using components the closest values available from the local RadioShack or current project stock.

For the RC snubber, a 10Ω, 10W resistor was soldered in series with a pair of 5nF capacitors in parallel (equalling 10nF or 10000pF). The RCD snubber was implemented using a 36kΩ resistor and a 10µF capacitor with diode. Figure 6-5 shows the modified circuit with both snubbers seperately.

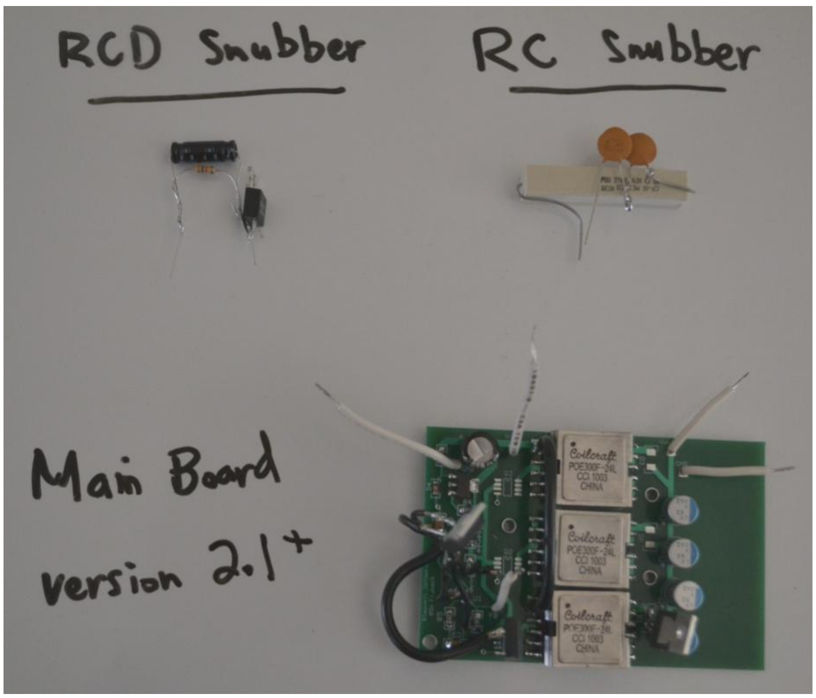


Figure 6-5: Circuit components with PCB

Figure 6-6 shows the PCB with both snubbers soldered, as well as the MOSFET IC driver in the foreground. Thicker gauge (14AWG) wires were also added to provide the lowest resistance path from the 48V input to the top of the primary side of the transformer, as well as the source of the MOSFET to ground.

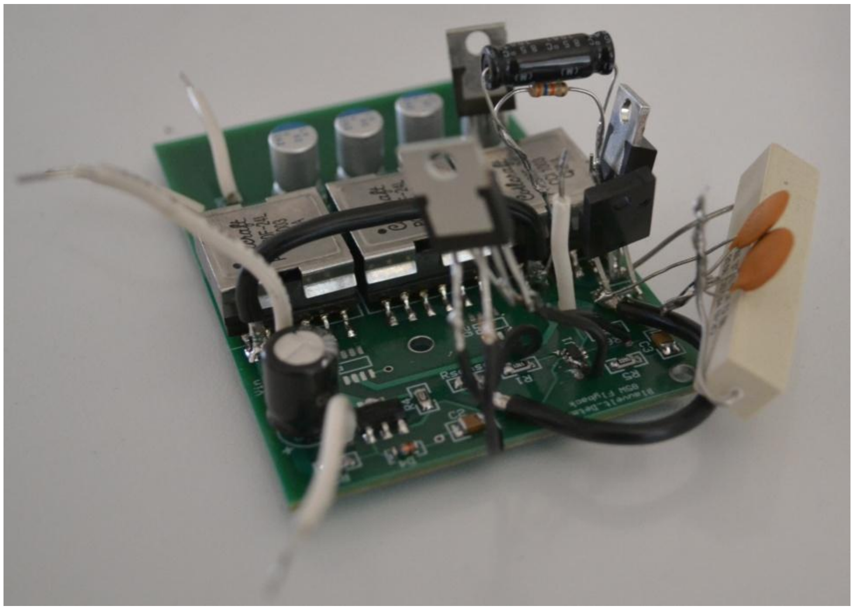


Figure 6-6: PCB modified for snubber testing

The addition of the snubbers and larger ground/power connections proved to be a successful solution to the crippling voltage spikes. At all output voltage levels, 0.5A output was possible with a reasonable voltage spike of 100V across V_{DS} of the MOSFET. Testing with both snubbers at a 5V output can be seen below in Figure 6-7.

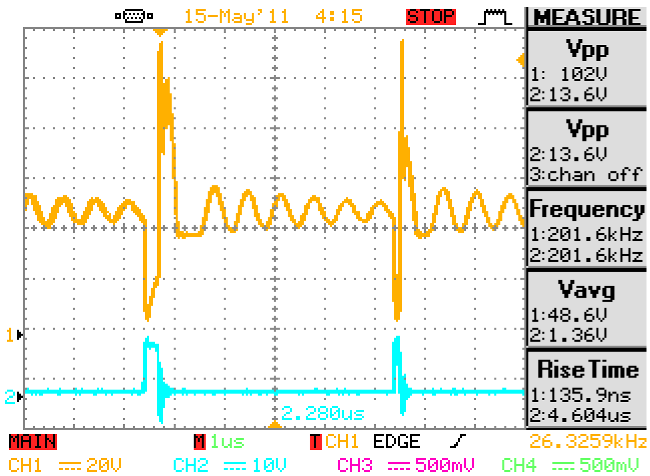


Figure 6-7: Modified PCB Testing; only RCD snubber (5V output at 100mA)

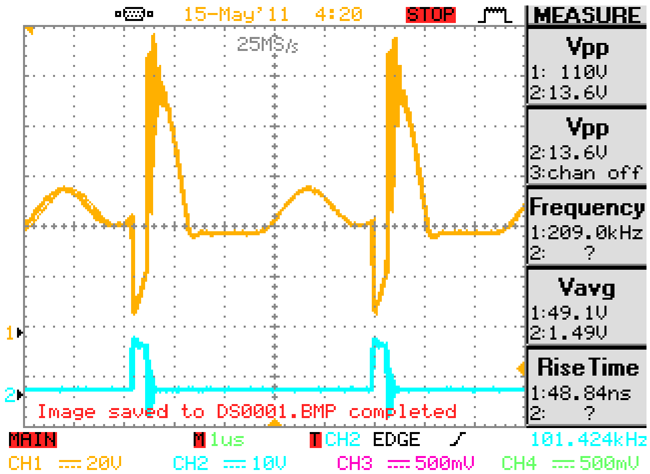


Figure 6-8: Modified PCB Testing; both snubbers (5V output at 100mA)

Testing demonstrated the designs for both the RC snubber as well as the RCD snubber were justifiable. As expected the RC snubber almost eliminated the voltage ringing at LC resonance, while the RCD snubber limited the voltage spike across the MOSFET. However during testing at an output of 24V, the RCD snubber proved to be ineffective and resulted in its overheating, caused by only having a rating of 1W. Figure 6-9 shows the test bench arrangement and a successful test at 12V out and 700mA load.

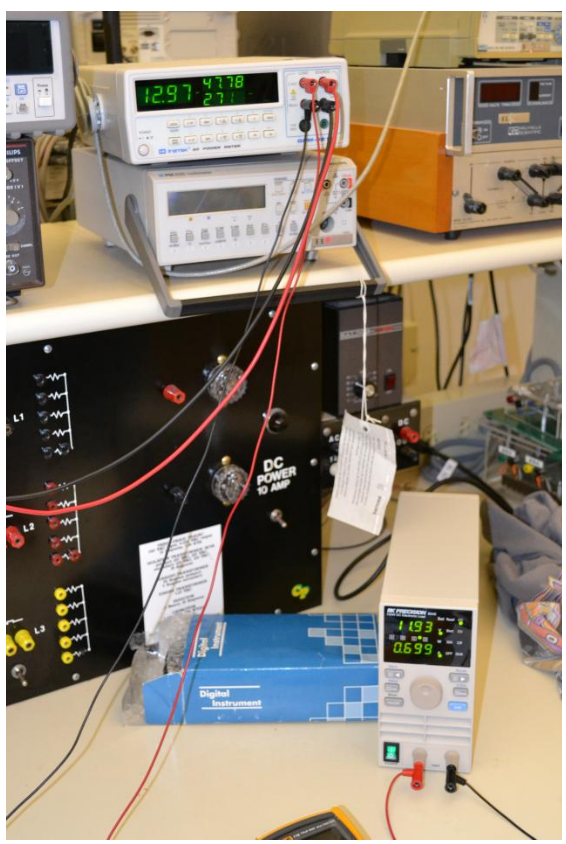


Figure 6-9: Modified PCB Testing at 12V output, 700mA

PCB Version 2.0

With a successful implementation of the snubbers and larger connections for traces, PCB redesign began. The second design was produced more rapidly due to few minor modifications required. The addition of snubbers, larger MOSFETs, and a MOSFET driver can be seen on the left side of the board in Figure 6-10.

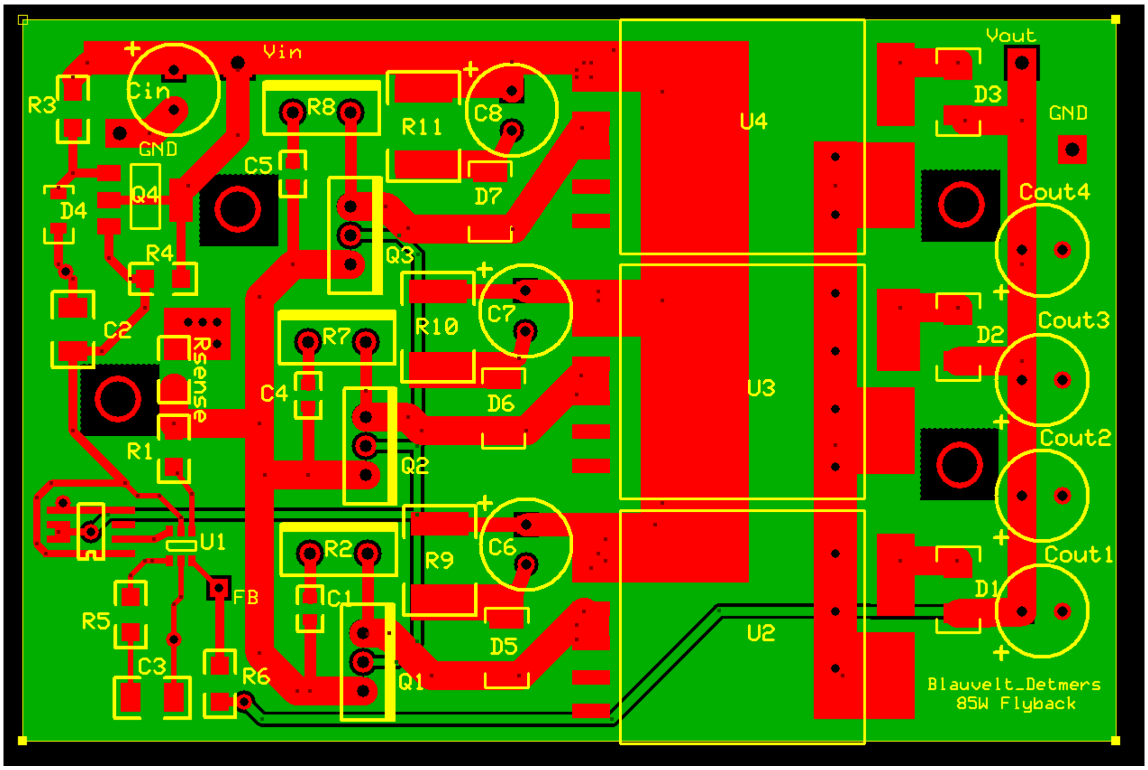


Figure 6-10: PCB Design, Version 2.0 (Added Snubbers, MOSFET Driver, and Larger Traces)

In addition to augmenting the current carrying traces, additional vias were created between ground nodes on the top surface and the bottom ground plane. The feedback control signal length was also minimized and routed as distant from the current carrying traces as possible in an effort to avoid EMI. The gate control lines were also moved away from large current-carrying traces to minimize switching noise.

Once the redesigned circuit board arrived from ExpressPCB and components from Digikey, the parts were mounted, and careful attention was given to avoiding cold solder joints, which would increase resistance and affect circuit performance. The new board mid-production can be seen in Figure 6-11.

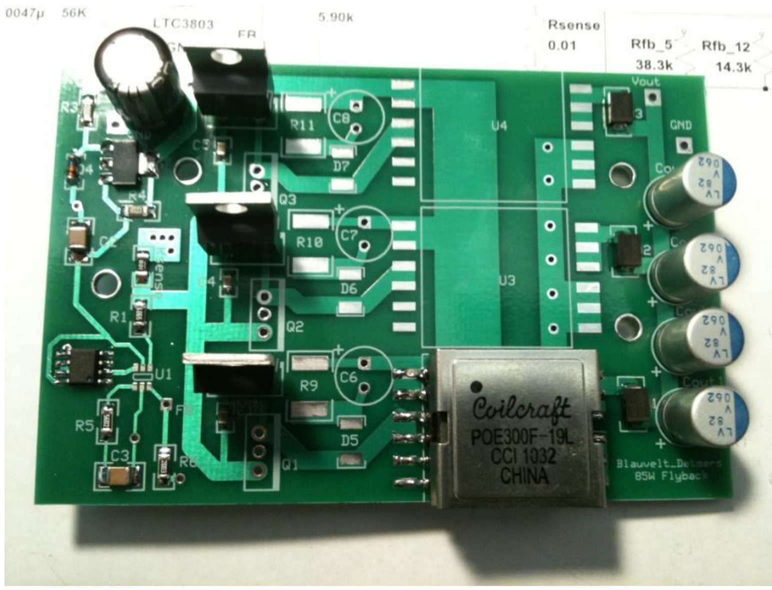


Figure 6-11: Version 2.0 PCB (Photo Taken Mid-Production to Show Trace Details)

Testing commenced in the same methodology used to test the previous version, starting with testing for given output voltages while changing feedback resistors. This again proved successful, so further observations were made with an oscilloscope to determine whether the Snubbers were functioning properly.

While setting the feedback resistor to give 12V output, the voltage on the MOSFET drain was observed with the scope. As can be seen from Figure 6-12, the drain voltage spike has been successfully supressed to 110V, which was acceptable with the new MOSFET's having a drain voltage rating of 600V. However, the LC ringing was still present after switch turn-off.

In addition, a new anomaly was present in that the switching frequency had changed to 100kHz. This was most puzzling since the LT3803 is only meant to operate at a switching frequency of 200kHz. This was noted and further observations were made.

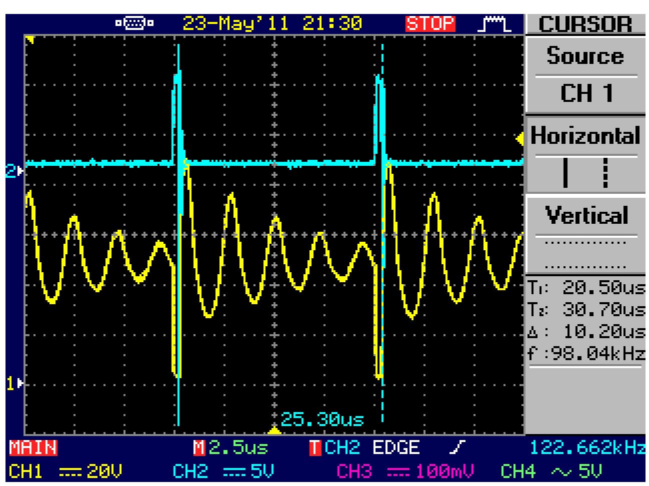


Figure 6-12: Version 2.0 Drain Voltage (CH1-Yellow) and Gate Voltage (Ch 2- Blue)

These results were disappointing at best, especially since the redesigned previous board had functioned far better with mis-matched components and excess wire leads. However, it was decided that testing continue to determine whether functionality of the outlet could be attained with these limited results.

Load testing commenced and the results of each can be seen in the Efficiency plots Figure 6-13a and 6-13b. Details of each plot can be found in Appendix D. The maximum load for 12V, 19V, and 24V was reduced to 1A, while the max load for 5V was reduced to 120mA as the converter would fail to respond at any loads above, and the switches would reach thermal breakdown.

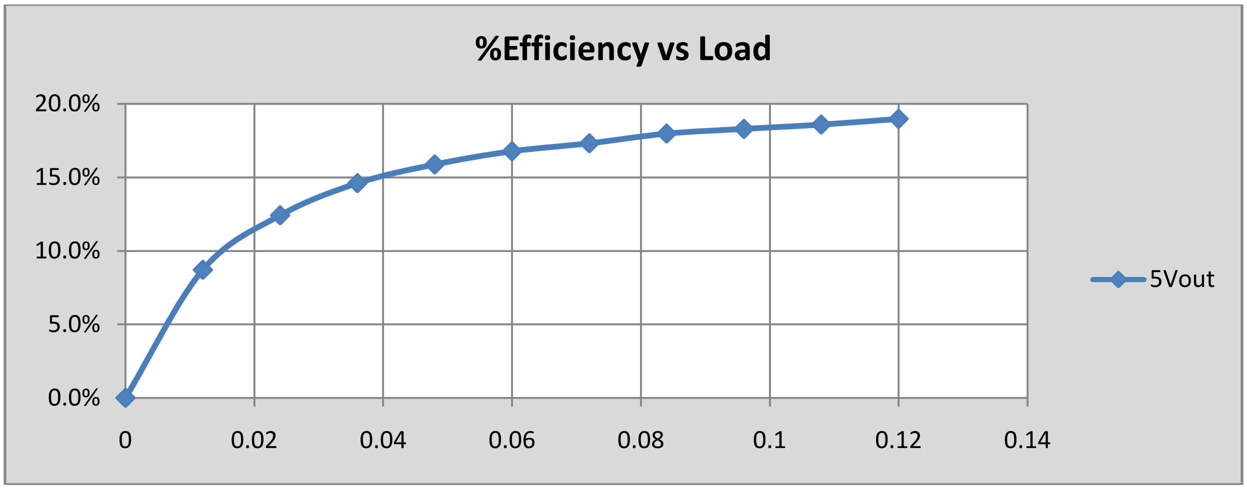


Figure 6-13a: Efficiency of 5Vout, Max Load of 120mA.

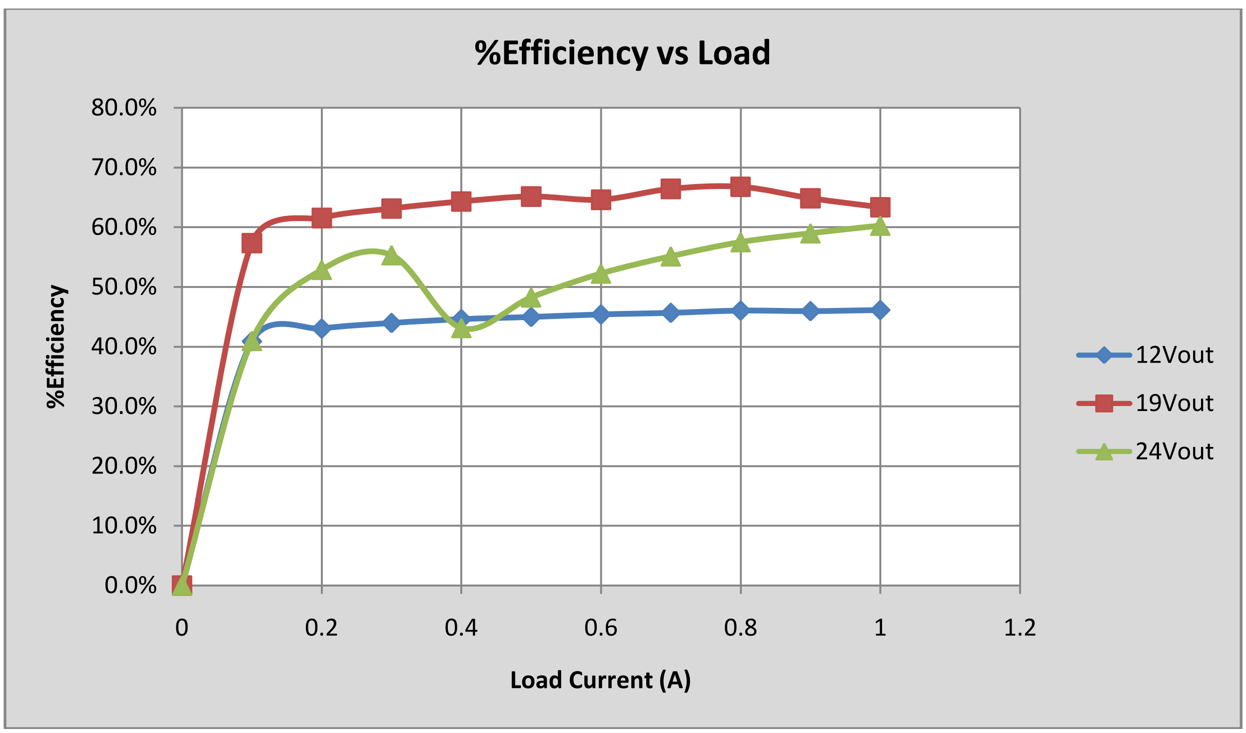


Figure 6-13b: Efficiency of 12V, 19V, and 24V Output, Max Load of 1A.

As a wide-input device, the converter was tested with input voltages ranging from 20% above and below the given 48V nominal that was set prior to project initiation. Figure 6-14 shows the Line Regulation behavior at each output voltage.

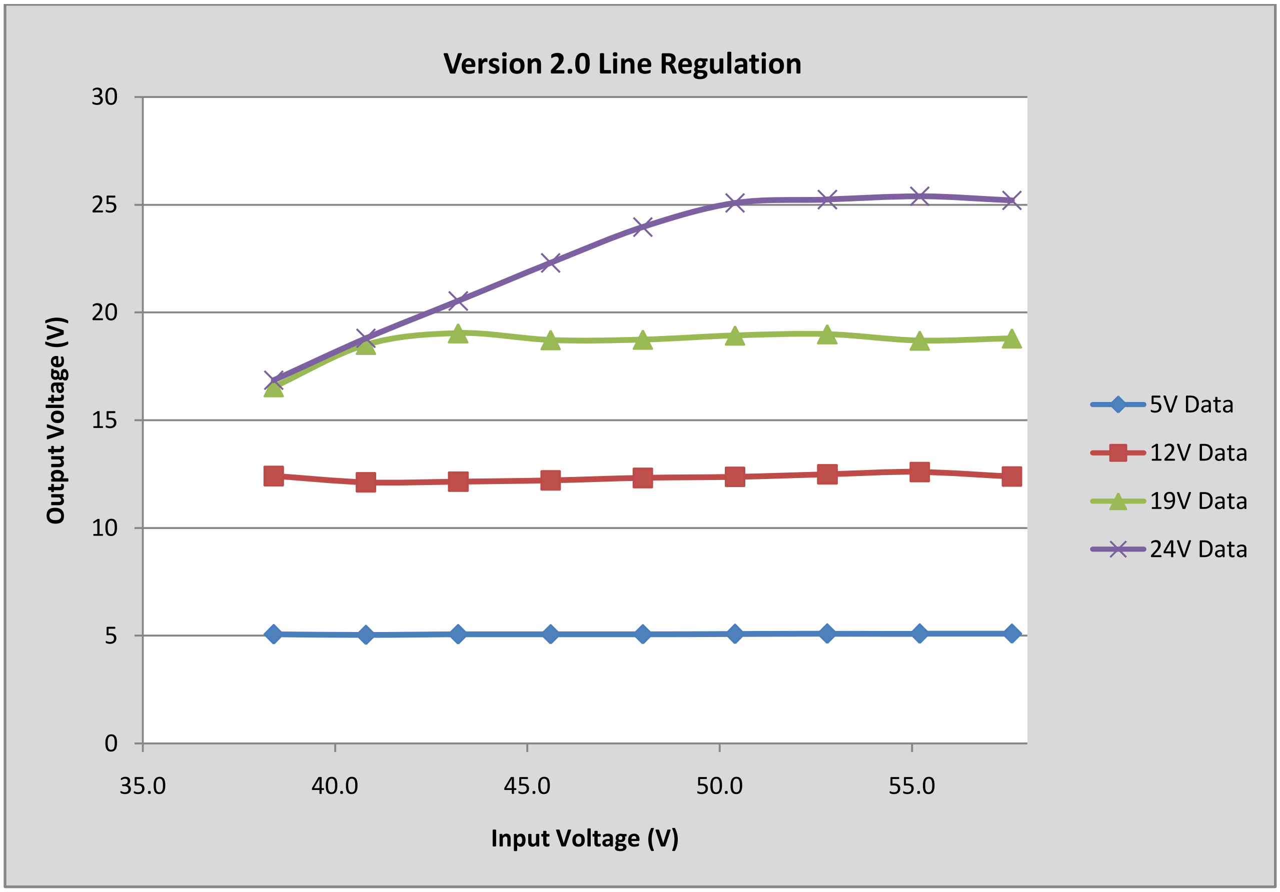


Figure 6-14: Line Regulation data for Version 2.0 PCB Design (±20% Nominal Input Voltage)

As seen from Figure 6-14, line regulation was improved at lower output voltages, however the 5V data is based on a full load of 120mA.

VII. System Integration

Once testing of the board was complete, mounting it into the outlet housing was simple and effective. A clear, hard-plastic cover was used to mount the circuit board inside the electrical box, and the outlet was mounted similar to standard 120VAC outlets with a cover cut from a standard wall outlet cover plate.

The switch was wired in between the input wire to provide another level of protection, even though the issue of open-feedback voltage spike on the output had already been resolved. The switch provides a means to prevent against "phantom energy use", as well as an added layer of protection between the user and the bus. The finished product can be seen in Figure 7-1 below.

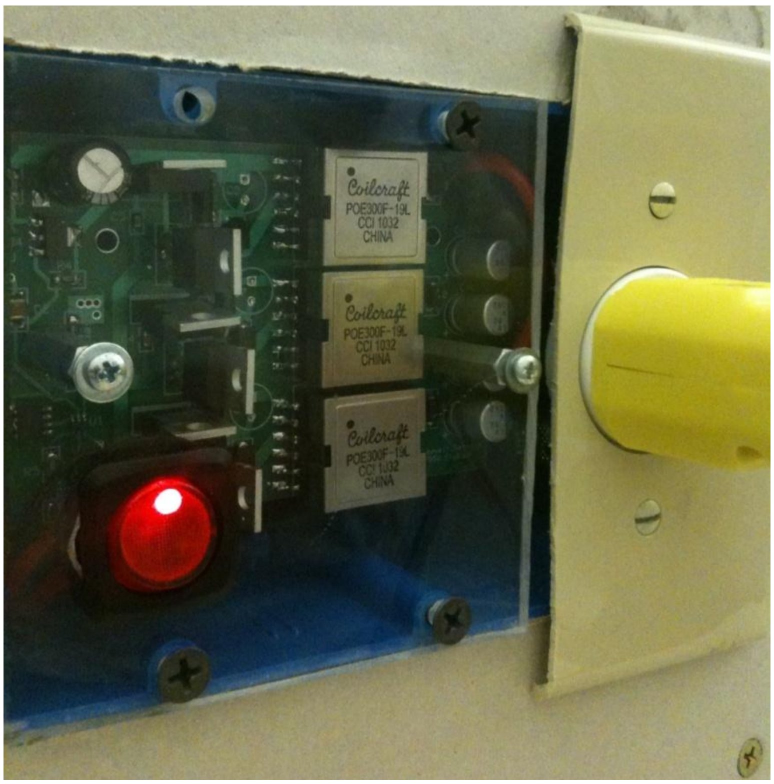
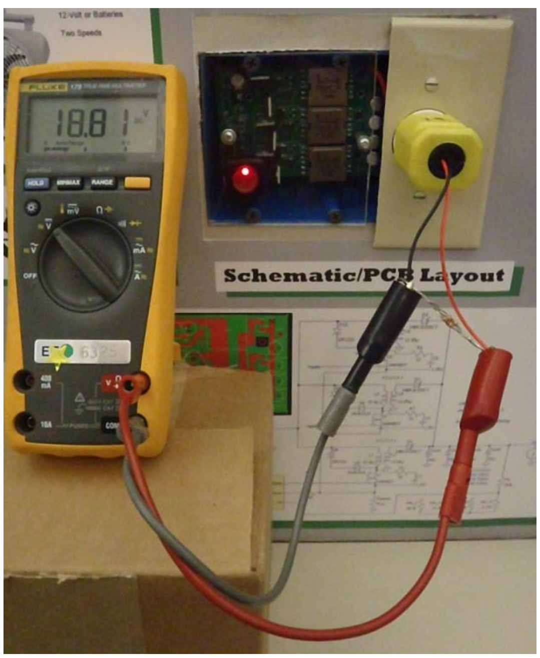


Figure 7-1: Mounted PCB installed in Electrical Box with Plug Inserted

As a final test, each plug was inserted into the outlet to check functionality of the feedback loop. This was successful in that each voltage was realized upon contact, and shows that the implementation of plug and receptacle both meet requirements. Figure 7-2 (a through d) shows an operational outlet at all four output voltages.

7-2a

7-2b



7-2c

7-2d

Figure 7-2: Outlet operating at a)5V; b)12V; c)19V; d)24V

In order to provide a demonstration, the outlet was mounted to a simulated section of house frame using 2x4' dimensional lumber, a common framing material, and a 4 square foot piece of sheet-rock (drywall), with appropriate hole cut for mounting. This demonstration shows the application of the outlet similar to a standard 120 or 24VAC standard outlet used in most countries.

VIII. Conclusions and Recommendations

Conclusions

Although this project was centered upon the system-level design of a multi-variable DC outlet, it became obvious that most challenging was designing a DC/DC converter that would handle such an arduous task. Most converters are assigned one output voltage, and the converter is designed with just that in mind. However, providing a robust enough converter for the project became the primary task at hand.

Throughout the many different designs and versions of this system, it was learned that there are a large number of issues that plague the operation of a Flyback converter. One of the largest concerns is the large voltage spikes across the main MOSFET switches due to leakage inductance of the transformers. Voltage spikes created problems for the initial design, leading to the premature failure of MOSFETs.

Despite many setbacks a resonably regulated output was achieved at all desired voltage levels, however adequate power supply was only at an output of 12V and 19V. At an output of 5V the circuit was only able to maintain an output of 120 mA (which is only 6% of the desired full load). At 12V and 19V a stable regulated output at 1A was achieved. At 24V the converter provided 1A output while the voltage started to sag.

Nevertheless, the feedback loop and plug design met the "ease-of-use" requirement as well as providing a multi-tiered level of circuit protection. If the plug is removed without turning off the main switch the voltage output will slowly ramp down to ~850mV.

Recommendations

Further redesigns would be necessary to achieve the requirements of maximum 3A output at all voltage levels. The snubbers added to resolve voltage spikes reduced the efficiency of the converter and increased board temperatures. Thus, later designs would need to look into more efficient board layouts as well as MOSFETs with lower R_{DS-ON}.

Future revisions to the outlet design should avoid using a Flyback converter due to the sensitivity to changing voltage outputs as well as high input current demands/voltage spikes on the main switch. Or, if the same design is used, a transformer that replaces the current triple-configuration should be used. A Forward converter would be a resonable alternative, as well as implementing a fully isolated circuit by utilizing a opto-isolator in the feedback loop.

The system met specifications and would need minimal modifications, the most important being a relay or sensing circuit to detect if current is being draw from the outlet. If no current was being consumed the circuit could safely enter a low power mode awaiting a plug connection, thus reducing phantom loads and reducing energy loss from the house that has very little energy to spare.

References

[1] World Energy Outlook, International Energy Agency, http://www.worldenergyoutlook.org/electricity.asp

[2] NFPA 70®: National Electrical Code® (NEC®) Softbound, 2011 Edition http://www.nfpa.org/onlinepreview/online_preview_document.asp?id=7011SB#

[3] Rashid, Muhammad H. *Power Electronics: Circuits, Devices, and Applications*. Upper Saddle River, NJ: Pearson Prentice Hall, 2004. Print

[4] Linear Technology. http://www.linear.com [Download of LTSpice, component datasheets]

[5] Linear Technology, "Adjustable Frequency Current Mode Flyback/Boost/SEPIC DC/DC Controller," LTC3805-5 Datasheet, 2008. [Online]. Available: http://cds.linear.com/docs/Datasheet/38055fd.pdf.

[6] Coilcraft, Inc. 30 W Flyback Transformers for PoE Plus Applications http://www.coilcraft.com/poe300.cfm#table?CFID=407178&CFTOKEN=86094662&jsessionid=f6307e53d4e96f6f177f

[7] Linear Technology, "Constant Frequency Current Mode Flyback DC/DC Controller in ThinSOT," LTC3803 Datasheet, 2003. [Online]. Available: http://cds.linear.com/docs/Datasheet/3803fc.pdf.

[8] Carl Nelson, "Application Note 19". Linear Technology. LT1070 Design Manual. June 1986. [Online] Available: http://cds.linear.com/docs/Application%20Note/an19fc.pdf.

[9] McMaster-Carr NEMA Plugs and Receptacles. http://www.mcmaster.com/#nema-style-connectors/=cfovsr [Plug purchasing]

[10] McMaster-Carr NEMA Plugs and Receptacles. http://www.mcmaster.com/#nema-style-connectors/=cfoucc [Receptacle purchasing]

[11] *CARLON 3-gang Plastic New Work Electrical Box*. Lowe's; http://www.lowes.com/pd_130774-223-BH353A_0__?productId=1013531&Ntt=3-gang&pl=1&currentURL=%2Fpl__0__s%3FNtt%3D3-gang

[12] National Semiconductor, *Power Designer , Number 114*, National Semiconductor, 2900 Semiconductor Drive, PO Box 58090, Santa Clara, CA, 95052, http://www.national.com/appinfo/power/files/national_power_designer114.pdf

[13] Switching Power Supply Design: Discontinuous Mode Flyback Converter: Michele Sclocchi, Application Engineer; National Semiconductor.

[14] Switching Power Supply Design: Continuous Mode Flyback Converter: Michele Sclocchi, Application Engineer; National Semiconductor.

[15] Flyback Convert Subber Design: Ridley, Ray, PhD.; Switching Power Magazine Designers Series XII. Oct. 27, 2009

[16] Physics Archives. http://www.physicsarchives.com/index.php/courses/470 [Figure 2]

[17] DC House Project: Providing Access to Electricity for the Unfortunates. Dr. Taufik, Cal Poly San Luis Obispo. http://www.calpoly.edu/~taufik/dchouse/

Appendix A: Hand Calculations for Flyback Converter

Voltage Input: $V_{i\,min} = 38.4\,V \quad V_{i\,nom} = 38.4\,V \quad V_{i\,max} = 57.6\,V$

Current Output: $I_{o\,min} = 0.125\,A \quad I_{o\,max} = 3.5\,A$

$$f_{switch} = 200kHz \quad \Rightarrow \quad T = \frac{1}{f} = 5\,\mu s$$

Transformer: $T_{efficiency} = 0.90 \quad N = 1.5 \quad L_P = 42\,\mu H \quad L_S = 18.67\,\mu H$

Diode: $V_{d\,fw} = 0.7\,V \quad R_{ds\,on} = 95\,m\Omega$

Component Requirements:

$$P_{o\,min} = \left(V_o + V_{d\,fw}\right) * I_{o\,min} \qquad P_{o\,max} = \left(V_o + V_{d\,fw}\right) * I_{o\,max}$$

$$V_{ds\,on} = \frac{P_{o\,max}}{(T_{efficiency} * V_{i\,min})} * R_{ds\,on}$$

$$V_{fm} = N * (V_o + V_{d\,fw})$$

$$V_{ds\,max} = \left(F_{spike} + 1\right) * (V_{i\,max} + V_{fm})$$

Duty Cycle and Switch Times:

$$D_{nom} = \frac{N}{N + \frac{(V_{i\,nom} - V_{ds\,on})}{V_o + V_{d\,fw}}}$$

$$T_{on\,min} = \frac{V_{fm} * T}{(V_{i\,max} - V_{ds\,on}) + V_{fm}} \qquad T_{on\,max} = \frac{V_{fm} * T}{(V_{i\,min} - V_{ds\,on}) + V_{fm}}$$

$$D_{min} = \frac{1}{T_{on\,min}} \qquad D_{max} = \frac{1}{T_{on\,max}}$$

Primary Currents:

$$I_{p-ripple} = (V_{i\,min} - V_{ds\,on}) * \frac{T_{on\,max}}{L_P}$$

$$I_{p-average} = \frac{P_{o\,max}}{(V_{i\,min} - V_{ds\,on}) * T_{efficiency} * D_{max}}$$

$$I_{p-min} = I_{p-average} - \frac{I_{p-ripple}}{2} \qquad I_{p-peak} = I_{p-average} + \frac{I_{ripple}}{2}$$

Secondary Currents:

$$I_{s-ripple} = \left(V_o + V_{d\,fw}\right) * \frac{(T - T_{on\,max})}{L_S}$$

$$I_{s-average} = \frac{I_{o\,max}}{1 - D_{max}}$$

$$I_{s-min} = I_{s-average} - \frac{I_{s-ripple}}{2} \qquad I_{s-peak} = I_{s-average} + \frac{I_{s-ripple}}{2}$$

Switch and Diodes:

$$V_{diode\,max} = \frac{V_{i\,max}}{N} + V_o \qquad P_{diode\,max} = I_{s-rms} * V_{d\,fw} * (1 - D_{max})$$

Output Capacitor:

$$C_{output} = \frac{I_{s-ripple} * T_{on\ max}}{0.25 * V_{ripple}} \qquad ESR_{max} = \frac{V_{ripple} * 0.75}{I_{s-ripple}}$$

$$R_{sense} = \frac{0.100}{1.1 * I_{p-peak}}$$

Appendix B: Python Calculation Code

```
#! /usr/local/bin/python
import math

#Givens
Vimin=38.4      #80% of Vin nominal
Vimax=57.6      #120% of Vin nominal
Vinom=48.0
Iomin=0.125     #Iout is 3.5A, however we have 3 transformers and switches
Iomax=3.0/3     #in parallel.  Thus, the Io for each is ~1/3 of expected.

fsw=200e3       #frequency of MOSFET
T=1/fsw                 #Period

Teff=0.95               #Transformer Efficiency
Vdfw=0.7                #diode forward drop
Rdson=0.045             #MOSFET resistance
Nps=1.785               #1/0.09=11.11  1/0.14=7.14  1/0.33=3.03  1/0.56=1.785  1/0.67=1.49
                        #Only the last two maintain continuous mode operation.
Lp=37.8e-6              #Primary Inductance
Ls=Lp/(Nps**2)                  #Secondary Inductance

Vrp=0.100               #voltage ripple
Vout=[5,12,19,24]       #voltage output

Rfb_base=200000                 #Feedback resistor (R2)

####### Continuous Mode Operation for Flyback converter ########
print ("     ------Continuous Mode------")
for Vo in Vout:
        Fspike=0.15     #voltage spike factor across diode

        Pomin=(Vo+Vdfw)*Iomin                   #Pout Minimum
        Pomax=(Vo+Vdfw)*Iomax                   #Pout Maximum
        Vdson=Pomax/(Teff*Vimin)*Rdson

        Vfm=Nps*(Vo+Vdfw)
        Vdsmax=(Fspike+1)*(Vimax+Vfm)

        Dnom=Nps/(Nps+(Vinom-Vdson)/(Vo+Vdfw))

        #Times
        Tonmin=Vfm*T/((Vimax-Vdson)+Vfm)
        Tonmax=Vfm*T/((Vimin-Vdson)+Vfm)
        Dmin=Tonmin/T
        Dmax=Tonmax/T
        #Primary Currents
        Ip_rip=(Vimin-Vdson)*Tonmax/Lp
        Ip_avg=Pomax/((Vimin-Vdson)*Teff*Dmax)
        Ip_peak=Ip_avg+Ip_rip/2
        Ip_min=Ip_avg-Ip_rip/2
```

```
    Ip_rms=math.sqrt(Dmax*(Ip_peak*(Ip_avg-Ip_rip/2)+1/3*(Ip_peak-(Ip_avg-Ip_rip/2))**2))

    #Secondary Currents
    Is_rip=(Vo+Vdfw)*(T-Tonmax)/Ls
    Is_avg=Iomax/(1-Dmax)
    Is_peak=Is_avg+Ip_rip
    Is_rms=math.sqrt((1-Dmax)*(Is_peak*(Is_avg-Is_rip/2)+1/3*(Is_peak-(Is_avg-Is_rip/2))**2))

    #Switch and Diodes
    Vdiode_max=Vimax/Nps+Vo
    Pdiode_max=Is_rms*Vdfw*(1-Dmax)
    Co=Is_rip*Tonmax/(Vrp*0.25)
    ESR=Vrp*0.75/Is_rip
    Rsense=0.100/(Ip_peak*1.1)

    print ("Vout        %.1f"  %Vo, "   V")
    print ("Vds        %.4f"  %Vdsmax, "V")
    print ("Dmin         %.4f"  %Dmin)
    print ("Dmax         %.4f"  %Dmax)
    print ("Ip-average   %.4f"  %Ip_avg, "A")
    print ("Ip-ripple    %.4f"  %Ip_rip, "A")
    print ("Ip-minimum   %.4f"  %Ip_min, "A")
    print ("Co         %.4f"  %(Co*1e6), "uF")
    print ("ESR         %.4f"  %(ESR*1e3), "mohm")
    print (" ")

####### Discontinuous Mode Operation for Flyback converter ########
print ("     ------Discontinuous Mode------")

Fspike=0.40       #voltage spike factor across diode

Vout=[5,12,19,24]                    #voltage output

for Vo in Vout:
    Pomin=(Vo+Vdfw)*Iomin                     #Pout Minimum
    Pomax=(Vo+Vdfw)*Iomax                     #Pout Maximum

    Vdson=Pomax/(Teff*Vimin)*Rdson

    Vfm=Nps*(Vo+Vdfw)
    Vdsmax=(Fspike+1)*(Vimax+Vfm)

    Klk=0.989
    WIptot=1/Klk
    Wfly=WIptot*Pomax/fsw
    Ddt=0.1
    Vfb=Nps*(Vo+Vdfw)

    #Times
    Tonmin=Vfb*(1-Ddt)*T/((Vimax-Vdson)*Klk+Vfm)
    Tonmax=Vfb*(1-Ddt)*T/((Vimin-Vdson)*Klk+Vfm)
    Dmin=Tonmin/T
```

```
        Dmax=Tonmax/T
        #Primary Currents
        Ip_peak=2*Wfly*fsw/(Vimin*Dmax)
        Ip_rms=Ip_peak/1.732*math.sqrt(Tonmax/T)
        Ip_dc=Pomax/(Vimin*Teff)
        #Ip_ac=math.sqrt(Ip_rms**2-Ip_dc**2)

        #Primary Inductance
        L_p=2*Wfly/Ip_peak**2

        #Secondary Currents
        Is_peak=Iomax*2/(1-Dmax-Ddt)
        Is_rms=Is_peak/1.732*math.sqrt(1-Dmax-Ddt)
        #Is_ac=math.sqrt(Is_rms**2-Iomax**2)

        #Switch and Diodes
        Vdiode_max=Vimax/Nps+Vo
        Co=Is_peak*Tonmax/(Vrp*0.25)
        ESR=Vrp*0.75/Is_rip

        print ("Vout     %.1f"  %Vo, "   V")
        print ("Vds     %.4f"  %Vdsmax, "V")
        print ("Dmin      %.4f"  %Dmin)
        print ("Dmax      %.4f"  %Dmax)
        print ("Ip-rms    %.4f"  %Ip_rms, "A")
        print ("Ip-dc     %.4f"  %Ip_dc, "A")
        print ("Ip-peak   %.4f"  %Ip_peak, "A")
        print ("Vdiode   %.4f"  %Vdiode_max, "V")
        print ("Co      %.4f"  %(Co*1e6), "uF")
        print ("ESR      %.4f"  %(ESR*1e3), "mohm")
        print (" ")

#LTC3803 Design parameters
print ("     ------LTC3803 Design parameters------")
for Vo in Vout:
        R1=Rfb_base/((Vo-0.8)/0.8)
        print ("Vout %.1f"  %Vo, "V")
        print ("  R2   %.1f"  %R1, "ohm")
print (" ")

print ("Rsense %.3f" %Rsense, "ohm")
print (" ")

#Switch Snubber Design
print ("     ------Switch Snubber Design------")
fr=2e6  #Assumed value for ringing frequency based on oscilloscope data from first circuit
L_leak=0.430e-6
Vdsmax= 90.84        #Assuming no excess voltage spike

R=2*3.1415926*fr*L_leak
C=1/(2*3.1415926*fr*R)
Psn=C*(Vdsmax**2)*fsw
```

```
print ("R     %.4f"  %R, "ohm")
print ("C      %.4f" %(C*1e9), "nF")
print ("Power  %.4f" %Psn, "W")
print (" ")
#RCD Clamp Snubber
print ("     ------RCD Clamp Snubber------")
Vdsmax= 90.84        #Assuming no excess voltage spike
Vx=0.5*Vdsmax

Pl=0.5*L_leak*Ip_peak**2*fsw
Psn_max=Pl*(1+Vdsmax/Vx)

R=2*Vx*T*(Vdsmax+Vx)/(L_leak*Ip_peak**2)

print ("R     %.2f" %R, " ohm")
print ("Power     %.3f" %Psn_max, "W")

#LT snubber
print ("     ------LT Zener Snubber------")
Vf=1     #should be less than this, worst case
Ipri=2.6 #Transformer Rating
Vz=62
for Vo in Vout:
    Pzener=(Vz*Ipri**2*L_leak*fsw)/(2*(Vz-(Vo+Vf)*Nps))
    Vsnub=(Vz-(Vo+Vf)*Nps)
    print ("P     %.2f" %Pzener, " W")
    print ("Vsnub  %.2f" %Vsnub, " V")
```

Appendix C: Version 1.4 Simulation Testing

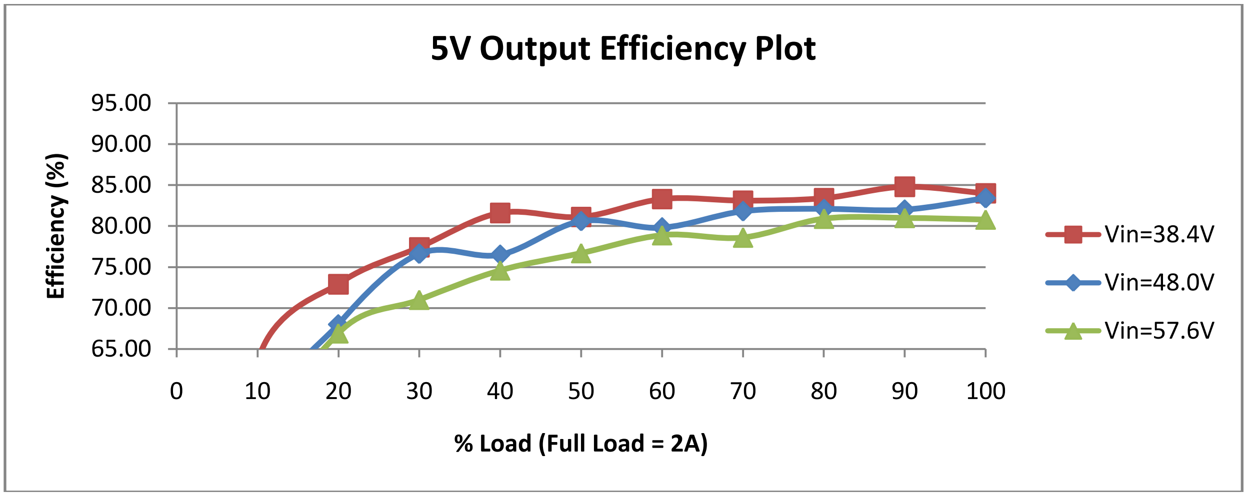


Figure C-1: Version 1.4 Efficiency vs %Load Plot, various input voltages showing line regulation, Vout =5V

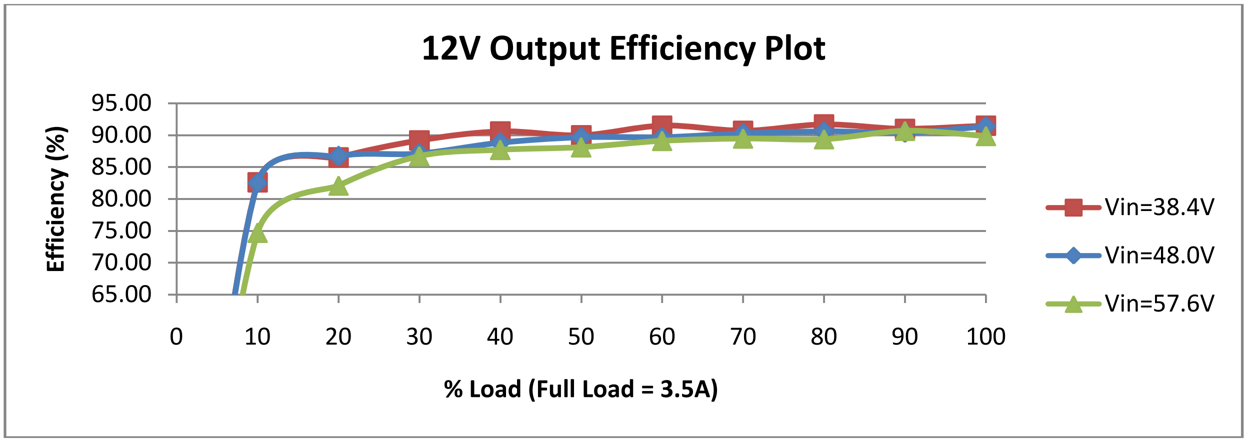


Figure C-2: Version 1.4 Efficiency vs %Load Plot, various input voltages showing line regulation, Vout 12V

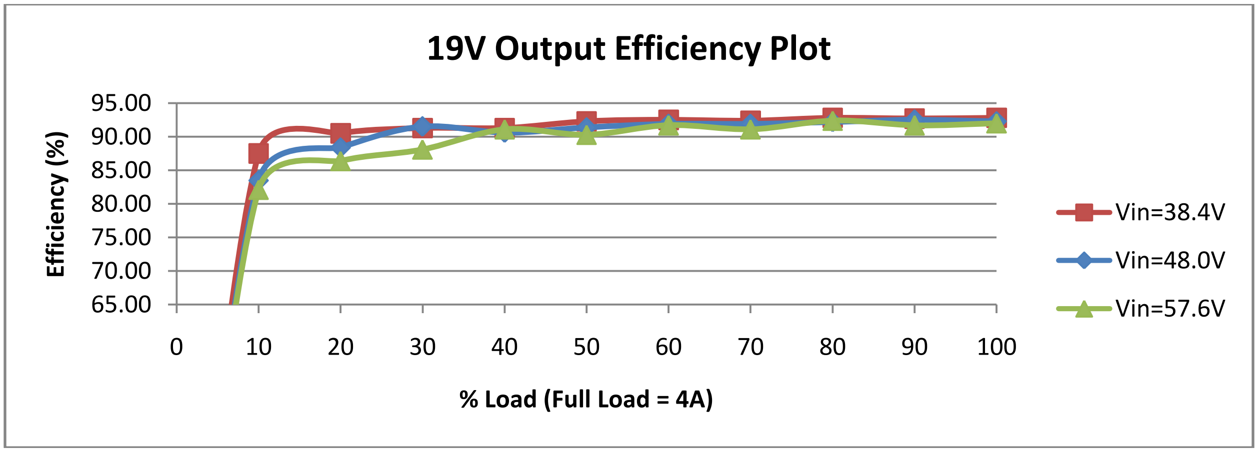


Figure C-3: Version 1.4 Efficiency vs %Load, various input voltages showing line regulation; Vout = 19V

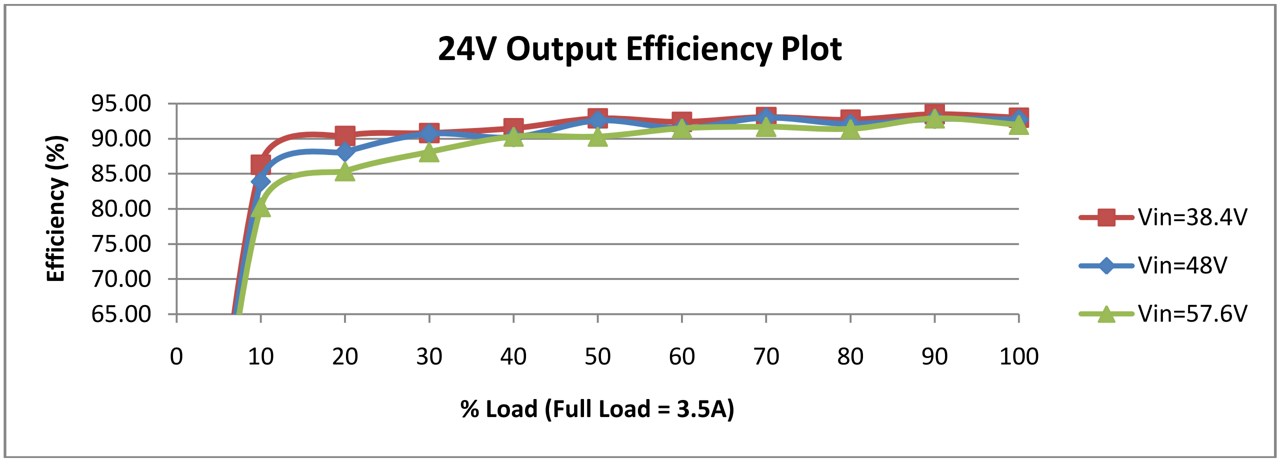


Figure C-4: Version 1.4 Efficiency vs %Load Plot, various input voltages showing line regulation, Vout = 24V

Appendix D: Efficiency Testing, Version 2.0 (Final), Table D-1

Vin	Iin (A)	Pin (W)	Vout (V)	Vout Ripple (V)	Iout (A)	Pout (W)	%Eff
48	0.0095	0.43	5.1	0.04	0	0	0.0%
48	0.026	0.7	5.08	0.05	0.012	0.06096	8.7%
48	0.036	0.98	5.07	0.04	0.024	0.12168	12.4%
48	0.034	1.25	5.07	0.04	0.036	0.18252	14.6%
48	0.04	1.53	5.06	0.04	0.048	0.24288	15.9%
48	0.045	1.81	5.06	0.04	0.06	0.3036	16.8%
48	0.05	2.1	5.05	0.036	0.072	0.3636	17.3%
48	0.056	2.36	5.05	0.036	0.084	0.4242	18.0%
48	0.063	2.65	5.05	0.04	0.096	0.4848	18.3%
48	0.078	2.94	5.06	0.046	0.108	0.54648	18.6%
48	0.078	3.2	5.06	0.048	0.12	0.6072	19.0%
48	0.01	0.43	12.3	0.1	0	0	0.0%
48	0.14	3.01	12.3	0.171	0.1	1.23	40.9%
48	0.181	5.73	12.32	0.186	0.2	2.464	43.0%
48	0.237	8.44	12.36	0.205	0.3	3.708	43.9%
48	0.29	11.1	12.37	0.208	0.4	4.948	44.6%
48	0.31	13.74	12.35	0.22	0.5	6.175	44.9%
48	0.422	16.44	12.43	0.233	0.6	7.458	45.4%
48	0.503	19.1	12.45	0.242	0.7	8.715	45.6%
48	0.584	21.7	12.48	0.25	0.8	9.984	46.0%
48	0.682	24.5	12.5	0.256	0.9	11.25	45.9%
48	0.741	27.2	12.54	0.27	1	12.54	46.1%
48	0.012	0.45	18.7	0.11	0	0	0.0%
48	0.166	3.27	18.75	0.184	0.1	1.875	57.3%
48	0.222	6.1	18.77	0.201	0.2	3.754	61.5%
48	0.302	8.94	18.81	0.216	0.3	5.643	63.1%
48	0.444	11.77	18.92	0.284	0.4	7.568	64.3%
48	0.408	14.54	18.94	0.284	0.5	9.47	65.1%
48	0.44	17.63	18.98	0.296	0.6	11.388	64.6%
48	0.44	20.3	19.26	0.25	0.7	13.482	66.4%
48	0.479	22.95	19.15	0.009	0.8	15.32	66.8%
48	0.53	25.4	18.3	0.012	0.9	16.47	64.8%
48	0.59	28.25	17.89	0.012	1	17.89	63.3%
48	0.018	0.5	25	0.1	0	0	0.0%
48	0.254	6.1	24.99	0.368	0.1	2.499	41.0%
48	0.328	8.73	23.08	0.48	0.2	4.616	52.9%
48	0.403	12.2	22.5	0.9	0.3	6.75	55.3%
48	0.474	22.72	24.5	0.006	0.4	9.8	43.1%
48	0.52	24.9	24.03	0.004	0.5	12.015	48.3%
48	0.566	27.1	23.6	0.005	0.6	14.16	52.3%
48	0.612	29.34	23.11	0.005	0.7	16.177	55.1%
48	0.66	31.56	22.69	0.004	0.8	18.152	57.5%
48	0.708	33.9	22.22	0.004	0.9	19.998	59.0%
48	0.753	36	21.7	0.005	1	21.7	60.3%

Appendix E: Component List for Project (Table E-1) (Items in red used in final design)

Item	Ordered From	U/P	Qty	Subtotal
Capacitor, Aluminum, 82uF, 35V	Digikey	$2.21	6	$13.26
Capacitor, Cer, 10uF, 25V	Digikey	$0.42	10	$4.18
Capacitor, Cer, 4700pF, 250V	Digikey	$0.46	3	$1.38
Diode, Schottky, 3A, 50V, DO-201 (SR305)	Digikey	$0.42	6	$2.52
Diode, Schottky, 3A, 50V, SMA (B350A-FDICT-ND)	Digikey	$0.66	6	$3.96
Diode, Zener, 8.2V, 1W, D041, (1N4738)	Digikey	$0.45	3	$1.35
Diode, Zener, 8.2V, SOD-80 (FLZ8V2CCT-ND)	Digikey	$0.39	3	$1.17
MOSFET, N-Ch, 150V, 8-SOIC (SI4848DY)	Digikey	$1.79	6	$10.74
Resistor, SMT, 1/4W, 1%, 0.01ohm,	Digikey	$1.12	3	$3.36
Resistor, SMT, 1/4W, 1%, 10.0kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 140kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 200kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 232kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 287kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 40.2kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 5.90kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 52.3kohm	Digikey	$0.10	3	$0.30
Resistor, SMT, 1/4W, 1%, 56.0kohm	Digikey	$0.10	3	$0.30
Resistor, TH, 1/4W, 1%, Metal Film, 10.0kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 140kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 200kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 232kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 287kohm	Digikey	$0.45	5	$2.25
Resistor, TH, 1/4W, 1%, Metal Film, 40.2ohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 5.9kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 1%, Metal Film, 52.3kohm	Digikey	$0.11	5	$0.56
Resistor, TH, 1/4W, 5%, Carbon Film, 56kohm	Digikey	$0.07	5	$0.35
Resistor, TH, Current Sense, 3/8W, 0.01kohm	Digikey	$0.52	5	$2.60
Transistor, NPN, 100mA, 350V, SOT223	Digikey	$0.59	3	$1.77
Transistor, NPN, GEN-PURP, TO-39	Digikey	$1.66	2	$3.32
Plug, Quick-Wire, Straight-Blade, 250VAC, 15A	McMaster	$6.72	4	$26.88
Receptacle, Straight-Blade, NEMA, 250VAC, 15A	McMaster	$13.48	1	$13.48
IC Driver, MOSFET, 6A, SOIC	Digikey	$1.04	1	$1.04
IC Driver, MOSFET, 9A, TO-220	Digikey	$4.07	1	$4.07
IC Driver, MOSFET, SGL, 9A, 8-DIP	Digikey	$3.64	1	$3.64
MOSFET, N-CH, 200V, 4.5A	Digikey	$1.08	6	$6.48
Drywall, 2'x2'	Home Depot	$4.25	1	$4.25
Wallplate, plastic, 3-gang	Home Depot	$1.98	1	$1.98
Wallplate, plastic, cover, 2 gang	Home Depot	$0.89	1	$0.89
Wallplate, plastic, cover, 3 gang	Home Depot	$1.48	1	$1.48
Wood, 2"x4"x8', (for framing)	Home Depot	$2.55	1	$2.55
Resistor, 10W, 10ohm	Radio Shack	$1.99	1	$1.99
Capacitor, disc, .005uF	Radio Shack	$1.79	2	$3.58
capacitor, disc, 10uF, 50V	Radio Shack	$1.19	2	$2.38
Switch, Neon, Rocker	Radio Shack	$4.19	2	$8.38
Custom PCB	ExpressPCB	$30.47	3	$91.41
Capacitor, Electrolytic, Radial, 160V, 10uF	Digikey	$0.40	3	$1.20
capacitor, Ceramic, 200V, 2200pF	Digikey	$0.38	3	$1.14

Diode, Schottky, 3A, 200V, SMB	Digikey	$0.79	3	$2.37
Diode, Zener, 62V, 5W, Axial	Digikey	$0.44	3	$1.32
Diode, Zener, 75V, 5W, Axial	Digikey	$0.44	3	$1.32
Heat Sink, TO-220, 0.500", compact	Digikey	$0.33	3	$0.99
IC Driver, MOSFET, 9A, 8SOIC	Digikey	$1.75	1	$1.75
MOSFET, N-CH, 650V, 31A, TO-220	Digikey	$7.58	3	$22.74
Resistor, 35W, 5%, 15ohm	Digikey	$3.60	3	$10.80
Resistor, Metal Film, 1/4W, 1%, 14.3kohm	Digikey	$0.15	2	$0.30
Resistor, Metal Film, 1/4W, 1%, 38.3kohm	Digikey	$0.15	2	$0.30
Resistor, Metal Film, 1/4W, 1%, 5.9kohm	Digikey	$0.11	5	$0.56
Resistor, Metal Film, 1/4W, 1%, 6.81kohm	Digikey	$0.15	2	$0.30
Resistor, Metal Film, 1/4W, 1%, 9.09kohm	Digikey	$0.15	2	$0.30
Resistor, SMD, 3/4W, 5%, 36kohm	Digikey	$0.43	3	$1.29
Capacitor, 4700pF, SMT	Mouser	$0.24	2	$0.48
Capacitor, 4700pF, Through-Hole	Mouser	$0.39	5	$1.95
Diode, 1N3547BRLG, 10V, 5W	Mouser	$0.40	2	$0.80
Diode, Schottky, 647-UKL1H100KDDANA	Mouser	$0.23	5	$1.15
Diode, Zener, 621-DFLZ10-7	Mouser	$0.58	4	$2.32
Electrical Box, Double Gang, NW	Ace Hardware	$1.49	1	$1.49
Electrical Box, Triple Gang, NW	Ace Hardware	$3.49	1	$3.49
MOSFET, SI4848DY, 150V, 3.7A, 3W	Mouser	$2.02	3	$6.06
Proto-Board Adapter, SOT-23-6	DigiKey	$2.07	3	$6.21
Resistor, 0.2ohm, 1%	Mouser	$2.26	2	$4.52
Resistor, 100 ohm, 5%	Mouser	$0.05	10	$0.50
Resistor, 18.2 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 2 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 30 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 30.1 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 38.3 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 56 kohm, 1%	Mouser	$0.06	10	$0.60
Resistor, 6.81 kohm, 1%	Mouser	$0.05	10	$0.50
Resistor, 8.06 kohm, 1%	Mouser	$0.08	10	$0.80
Proto-Board Adapter (Breakout) SOT-23-6	Digikey	$2.07	3	$6.21
Custom PCB	ExpressPCB	$30.47	3	$91.41

Total Cost of Final Design (Components, Board, Box, Outlet, and Plugs): $106.29

Appendix F: ABET Senior Project Analysis

Requirements

The purpose of the Variable Output DC outlet is to provide an easy-to-use source of power for individual loads inside the DC house. The maximum output of the outlet will be less than 90W. The system will allow for an output of 5V, 12V, 19V, and 24V. Isolation will be attained by use of an isolated converter topology such as a Flyback, switching DC-DC converter design implementing output voltage control feedback loop with a non-isolated feedback loop. The printed circuit board will be created in a PCB editor and sent to a professional PCB etching company to ensure a low-noise, highly-efficient operation. Most discrete components will be surface-mounted to increase efficiency and reduce size of the board such that the entire converter will fit into a 3-gang, plastic, old-work or new-work electrical box. The plug going into the outlet requires a selector pin that will change the output voltage of the device by changing the feedback loop depending on pin placement. A power switch will be incorporated into the face of the outlet to provide a safety mechanism that allows the input to be completely disconnected when no load is present. The separation of the power contacts of the plug must have a separation that, at minimum, abides by the National Electric Code to prevent arcing and fire hazard [2].

Primary Constraints

The primary constraint in this project is the physical design of the isolated converter. The chosen topology of the Flyback converter presents numerous inherent design impracticalities which hamper the operation of the outlet. For example, the functionality of the LT3803 Flyback Controller used in this converter depends highly on the low sense resistor value (20 mohm) which determines the current limit behavior of the controller. In addition, the inherent leakage inductance existing in each transformer creates hazardous voltage spikes on the drains of the MOSFET's which strain the dielectric inside and causes breakdown at higher loads.

It could be possible to use a different controller available from another manufacturer; however the expense would be in terms of simplicity and ease of simulation of the circuit, as LTSpice has built-in libraries of all their parts in their software. In addition, different transformers could be used that limit leakage inductance and offer higher power rating, eliminating the need for three separate transformers.

Economic

The original estimated cost of this project was approximately $75, accounting for professionally-made PCB's, surface-mount and thru-hole components and hardware for the plug/outlet interface. The actual final cost was $106.29, due the excess cost of the receptacle, snubber circuit components and high-rated MOSFETs. The final bill of materials can be seen in Appendix E of the report.

During the development stage, $410.98 was spent on prototyping components, two separate PCB designs from ExpressPCB, as well as extra hardware needed for assembly. The development time was estimated at about 150 hours initially, but quickly added up to over 200 hours of work between both project team members. This was primarily due to the unexpected malfunction of the first PCB, and the subsequent redesign.

Commercial

If the outlet were manufactured on a commercial basis, it would be correlated with the number of DC Houses constructed and the need for power throughout each house. For example, if the DC House were to supply 300W total, there would need to be at least four outlets at 90W each if full load were to be drawn at any given point.

The manufacturing cost would be much lower than the prototyping cost due to the available highly-efficient production mechanisms for making circuit boards. In addition, the cost of parts would drop with production-quantity discounts given at most part retailers.

Purchase price for the outlet would have to be low enough to allow for purchase by the low-income families that would most likely be attempting to buy or build a DC House. This concept stems from the sole purpose of the DC House being available to towns and villages that cannot afford to purchase power from the local utility. This price would also determine the profitability; however this contradicts the idea of the DC House as being a low-cost solution for electrifying areas of the world where transmission of grid power is unavailable. Most likely any entity that would be providing products and services of this kind would be non-profit businesses, existing solely for the purpose of promoting renewable energy in developing countries.

The cost of operation would be negated once the entire DC House system is purchased, as off-grid users would not be purchasing power from any subscription-based utility.

Environmental

The environmental impact of producing the outlet would be the same as most electronic devices. All parts used are RoHS compliant, meaning they are free of hazardous substances. The circuit board can be recycled using modern PCB recycling methods for recovering valuable metals and other materials. Additionally, the receptacle and electrical box can both be used in other applications and are not specific to this design.

Manufacturability

The PCB used in the design of the outlet is a standard, double-layer board, and could be easily produced by automated processes should large-scale production be warranted. The resulting printed circuit board assembly could also be produced by automation, and thus reduce both production time and cost substantially.

The most significant challenge in manufacturing the outlet is final assembly inside the electrical box, which could possibly be done manually using its current setup. However, future design revisions could take into account better connections and mounting options thus making the installation process more efficient by means of automation.

Sustainability

Referring to the "Four E's of Sustainability:" Energy, Environment, Economics, and Equity, the DC House Project is an ideal example of using these concepts together in order to improve the health, comfort, and safety of many through the use of renewable energy.

The outlet is primarily focused on delivering the energy collected by photovoltaic (or other renewable source) to the customer. The key to making this a feasible transfer is by maintaining high

converter efficiency. This project did not attain the desired efficiency, but future modifications will ensure the effective delivery of power with minimal loss from the circuit.

As mentioned above, all the parts used in the outlet are RoHS compliant, and by using the minimal number of components without adding superfluous functionality, the outlet is an environmentally-friendly device. In addition, the materials used are easily recycled by modern electronics reclamation facilities.

With the generation of personal power comes the added benefit of reduction of power costs from a utility. Once a DC House system is installed, the upfront price is the only real cost to the consumer. The outlet requires minimal maintenance, and would ideally have a lifetime of over 20 years, given proper operating conditions.

The benefits of using the DC House with the Variable Outlet has equitable benefits the world over, as the adoption of this technology will lead to further developments in low-power appliances, reduced greenhouse gas emissions, less accidents from fuel handling, and less sickness from generator emissions. By implementing this kind of technology in developing nations, the idea of renewable energy would be gradually implemented and accepted as the country grows economically and industrially.

Ethical

The Variable DC Outlet was constructed with the highest ethical considerations in mind, as it is part of DC House project which aims to bring clean, renewable power to those unfortunate enough to go without.

As with the case of any electronics project, the impact of harmful chemicals was taken into consideration and minimized with the use of RoHS compliant parts, and hardware that is easily recyclable and reusable for other applications.

Health and Safety

As with any electrical device, the main health risk is electric shock. Several measures were taken in this project to ensure the safety of the user. With a Flyback converter, the risk of damage to the circuit and possible electric shock of the user occurs when the feedback loop is left open. This is prevented in the outlet by the rearrangement of the feedback voltage divider such that the loop is always closed, and if no plug is present, the output remains a safe, low voltage level. A second precaution was implemented with a switch on the front cover of the outlet which breaks the input to prevent power drain and protect from heating issues.

One possible concern is the misuse of the voltage-setting plugs associated with the outlet. In future designs, a system should be implemented which makes it simple for the user to employ the plugs with any available DC appliance in a safe and secure way.

Other safety concerns can be related to standard 120VAC outlet operation and are not unique to the Variable DC Outlet.

Social and Political

With over 1.4 Billion people living on this Earth without electricity, and the looming concerns of global climate change from the use of fossil fuels, the social implications of developing this project in conjunction with the DC House are overwhelmingly positive. The DC House promotes both providing electricity to those who need it most, as well as supplying it sustainably with renewable sources.

Every year, governments around the globe write legislature for new incentives for development of renewable resources. As a result of this, the solar industry alone has grown by 847% from 2000 to 2007[17]. This, coupled with the increased interest in decreasing the reliance on hydrocarbon-based energy sources, the case for implementing renewable energy sources on global scale is stronger than ever before.

Development

In the development of the Variable DC Outlet, development of the Flyback converter was largely based on knowledge gained during independent research during the pre-design phase of the project. This was primarily due to the limited material taught during courses in the curriculum regarding the actual use of Flyback converters and they're behavior during operation.

Most simulation techniques came from knowledge from courses in which LTSpice was primarily used. The development methods of the circuit board consisted of hand-solder and reflow-solder, the latter being self-taught during the course of the project. In addition, the extent of knowledge needed for routing traces and pads on the PCB was not acquired during courses, but learned through trials and much research into design rules and techniques.