Isolated Power Supply for Guitar Pedals

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Abstract

In the world of audio, power isolation is key for maintaining clean signals across the numerous devices that make up any signal chain. For many guitarists, this means providing maximally clean, isolated power to any number of guitar pedal effects units. Our isolated power supply means to be an efficient option for providing power to these pedals, accommodating a large range of voltage and current specifications. We mean to provide a consistent power source that can handle anywhere from small undersupplied low-current analog circuits, to large high-current digital circuits. This document will cover our design from initial conceptualization, to final design, and on further to subsequent improvements that might be made in the future.

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Introduction

Problem

Guitar players and other instrumentalists often use audio effect boxes, usually referred to just as guitar pedals. These pedals require supply generally at 9V, 12V, 15V, or 18V with current requirements ranging from 100mA up to 1000mA (in the case of some digital effects units). "Clean power" is the major requirement in these supplies, this means decoupling from AC sources and minimization of noise. Supplies for these pedals also need to have many outputs, as many pedal boards (collections of pedals used in series for one audio signal), have a number of individual units all requiring their own power. Most pedal power supplies on the market are quite expensive, don't always supply the exact combination of required output voltages, and don't have options to vary the output voltages for stylistic purposes. Stylistic variation in supply voltage refers to underpowering, and is used often by effects units to vary normal operation of external effect units. This power "sag" function mimics supply from a dying 9V battery.

Solution

Our isolated power supply solution is meant to be powered by connection to a standard U.S. wall outlet at 120V and 60Hz, as is available to the average consumer. Our system first converts AC to DC, stepping down voltage and current, and then follows an additional stage of DC to DC conversion. Both of these stages provide ground isolation from the previous source. Outputs are available at DC 9, 12, 15, and 18V. A variable "sag" control is built into the 9V output, allowing for user adjustment anywhere from 2V to the full 9V.

While similar devices exist online such as MXR [1] and Voodoo Lab [2], we had the goal of creating a more precise output by reducing the ripple, and including the option of purposeful undersupplying of voltage to one of the outputs to create a "dying battery" sound option for stylization purposes. We also focused on isolation, both in terms of noise and power.

For a clear view of our device concept, Figures 1.1 and 1.2 provide a look at our original and revised block diagrams respectively. Both block diagrams follow the same overall flow of power, with some revisions for efficiency in the latter figure. This document will provide a guide through our initial design process, all changes made over the course of testing and development, and what improvements might be made in a future implementation.

Design

Block Diagram

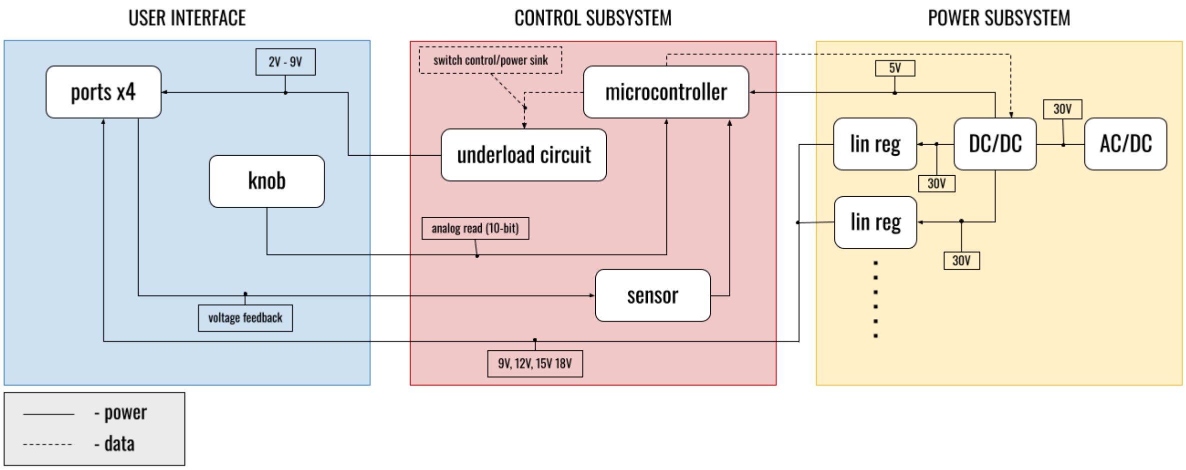

Figure 1.1 Original block diagram

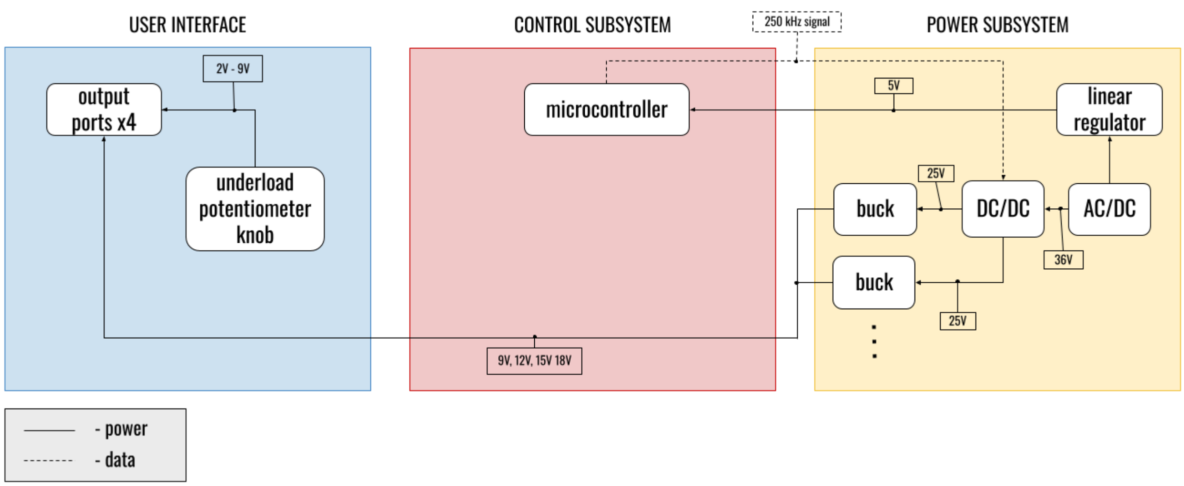

Figure 1.2 Final block diagram

Design Procedure

In both block diagrams, we can see that voltage goes from the wall AC power, is stepped down by an AC/AC transformer before encountering an isolated AC/DC rectifier, bringing it to DC voltage, and isolating it from the noise from the outlet. Power then flows into an isolated DC/DC converter, doubling down on the isolation of the first stage. Isolation in both of these converters comes from a transformer implemented into the converter to isolate from both noise and power domains. After the isolated DC/DC converter, we split off into four other DC/DC conversions, each one with the purpose of bringing down the voltage to the expected output voltages for the user to interact with. In our original plans, shown in Figure 1.1, we planned to implement this last line of DC/DC conversion via linear regulators, but we can see in Figure 1.2 that the linear regulation has been reserved only for powering the microcontroller, with all other outputs instead being replaced by buck converters. This choice was made to reduce loss, when compared to some commercial products such as Voodoo Labs [3], with the hope of therefore reducing heat within the system.

Originally, the microcontroller was meant to also control the underloading circuit, but a more simplified plan of placing a large potentiometer in place was determined to be the more efficient option in terms of response timing.

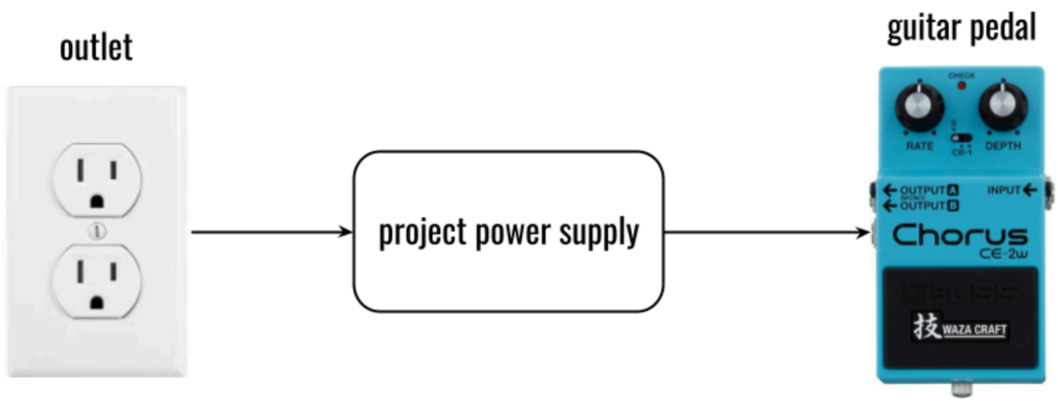

Figure 2.1 Visual aid of product

Design Details

As is shown in Figure 2.1, the design begins by a plug to wall power, at U.S. standard 120VAC and 60Hz, and is then passed through an AC/AC transformer to step down. Continuing, AC/DC converter is relatively straightforward, as shown in Figure 2.2, using a full bridge rectifier and a filter to obtain a DC output. The full subsystem includes a transformer to step down from 120 Vrms to a more reasonable 40 Vrms, a diode bridge, and then a large LC filter to smooth out the signal. This would bring us from an outlet to a lower DC voltage that we use to further step down. This would go from the AC voltage of 120 V from the wall down to around a 39 V DC output.

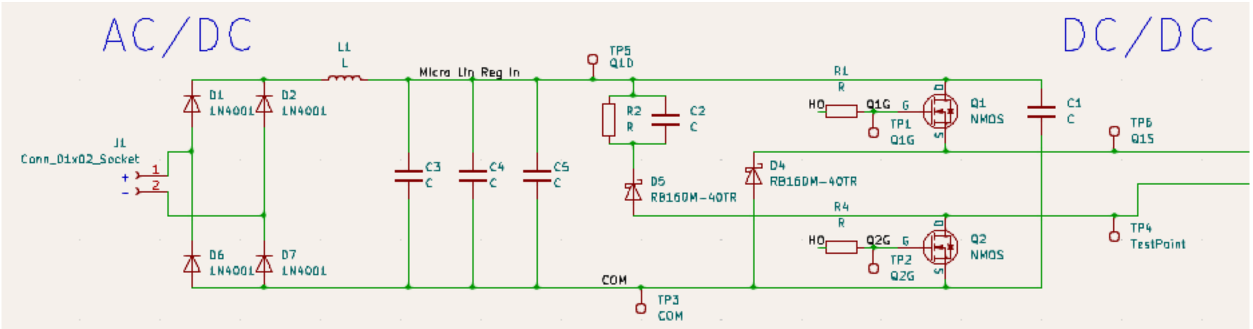

Figure 2.2 PCB schematic of AC/DC rectifier connecting to DC/DC switching

The goal is to have an isolated DC/DC converter that steps through to the same voltage. This voltage will then be directed into four step down converters, each set to step down to as close to 9V & 12V, and 15V & 18V as possible. In order to step down to four different levels, we used integrated buck converters since they are able to step down the voltage without the need for external control signals. They can also perform this task at a relatively high efficiency, reducing the risk of heat. The schematic for the isolated converter was initially a two switch flyback converter, as seen above in figure 2.2, with an RC clamp connected to one of the diodes as a safety measure. The two switch flyback uses a diode path to keep the transformer connected to the input voltage, even after the switches are turned off. This is required since the transformer is inductive and has leakage inductances that cannot be left without a path, otherwise this will cause issues in the circuit. Putting this diode path in a loop with the input voltage also induces a proper way for the leakage inductance to discharge the energy that builds up while the switch is on. This inductance needs to be kept in discontinuous conduction mode, otherwise the continued buildup of energy in this inductance will cause the transformer to act like a short, causing current surges. The microcontroller in this subsystem to be used for controlling the switches needed to run the isolated DC/DC converter. In order to determine the output we can get, we can use the ideal flyback conversion ratio:

$$V_{out} = \frac{D}{1-D}\frac{N_2}{N_1}V_{in}$$

Equation 1. Flyback conversion equation

Because of the issue that comes with the transformer's inductance, the duty ratio cannot be set any higher than 0.5, so that the inductance is not left continuously charging up. This means the maximum conversion we can achieve is done entirely through the turns ratio of the transformer.

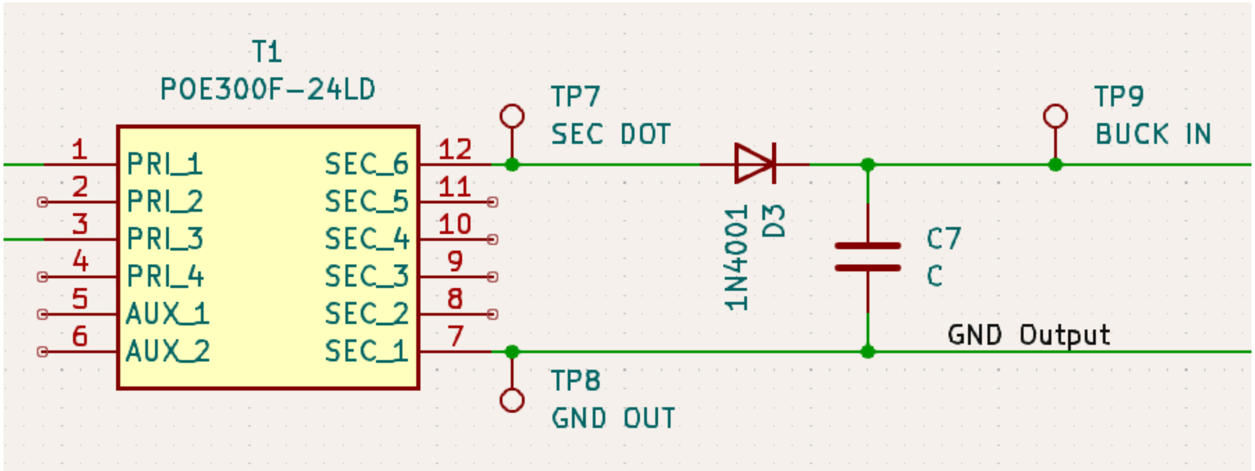

Figure 2.3 PCB schematic of DC/DC transformer as input to buck converters

For this subsystem we will need a flyback transformer, as shown in Figure 2.3, which is built to minimize leakage inductance, reducing the risk of putting the leakage inductance in CCM. We will also need capacitors, resistors, diodes, and switching MOSFETs. Given the 500mA maximum output for each port, the components should be rated for 2 amps of current at the minimum.

Moving to the next subsystem, after isolating and stepping down the voltage, we need to split up and step down this voltage to four different levels. As mentioned in the previous subsystem, we are feeding 24 volts from the flyback. In order to step this down to outputs ranging from 9 to 18 volts, we will need separate step down converters. Initially we planned on using a series of linear regulators to step down to different voltages, however this would cause greater conduction losses as we try and step down to lower voltages. To avoid this issue we will instead be using buck converters. On the actual PCB we implemented buck ICs, which contain the required switching logic to operate as a buck converter. We can begin to set the required duty ratio for each output by using the ideal buck conversion ratio:

$$V_{out} = DV_{in} \Rightarrow D = \frac{V_{out}}{V_{in}}$$

Equation 2. Buck conversion equation, converted into a duty ratio equation

The buck ICs do not have pins to directly input a frequency and duty ratio. Instead, the logic works off an on timer that is set by a resistor placed across the voltage input and SD pins, as seen in figure 2.4. This in timer is followed by a 260 nanosecond off timer. This means we can control the duty ratio by setting the on time in relation to this set off timer. By using our require duty ratio and this set off time, we can find the on times needed for each output using this equation:

$$D = \frac{t_{on}}{t_{on}+t_{off}} \Rightarrow t_{on} = \frac{D}{1-D} t_{off}$$

Equation 3. The general equation for a duty ratio, converted into an on time equation

Once these on times are determined, we can use it alongside the input voltage coming out of the flyback in order to determine this on time set resistor value using the equation found on the data sheet:

$$R_{on} = \frac{(t_{on} - 67\epsilon{-}9)(V_{in} - 1.4)}{1.18\epsilon{-}10} - 1400$$

Equation 4. Equation for the on time resistor for the buck IC

With calculated values for the on time resistors for each output, these can then be set using potentiometers. The output from each of the four buck converters can then be fed into the underload circuit/output ports.

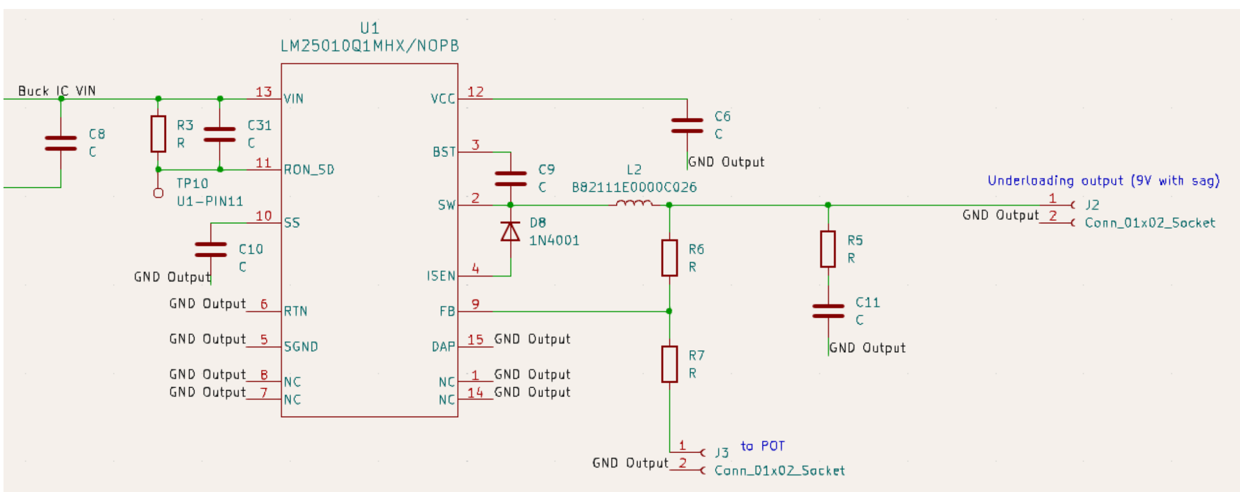

Figure 2.4 PCB schematic of buck converter showing 9V output, connection to underload potentiometer

The undersupply/underload portion shown in Figure 2.4 works to mimic a dying 9V battery for a stylistic effect. This portion is attached to the 9V output, where there is a physical knob a user can turn to get the effect, being able to sag down to 2 volts. We initially planned on using the microcontroller to control a current sinking device, such as a MOSFET, however for the sake of simplicity we replaced this with a potentiometer in series with the 9V output. The knob of the potentiometer is then attached to the enclosure itself, with marking for different voltage levels.

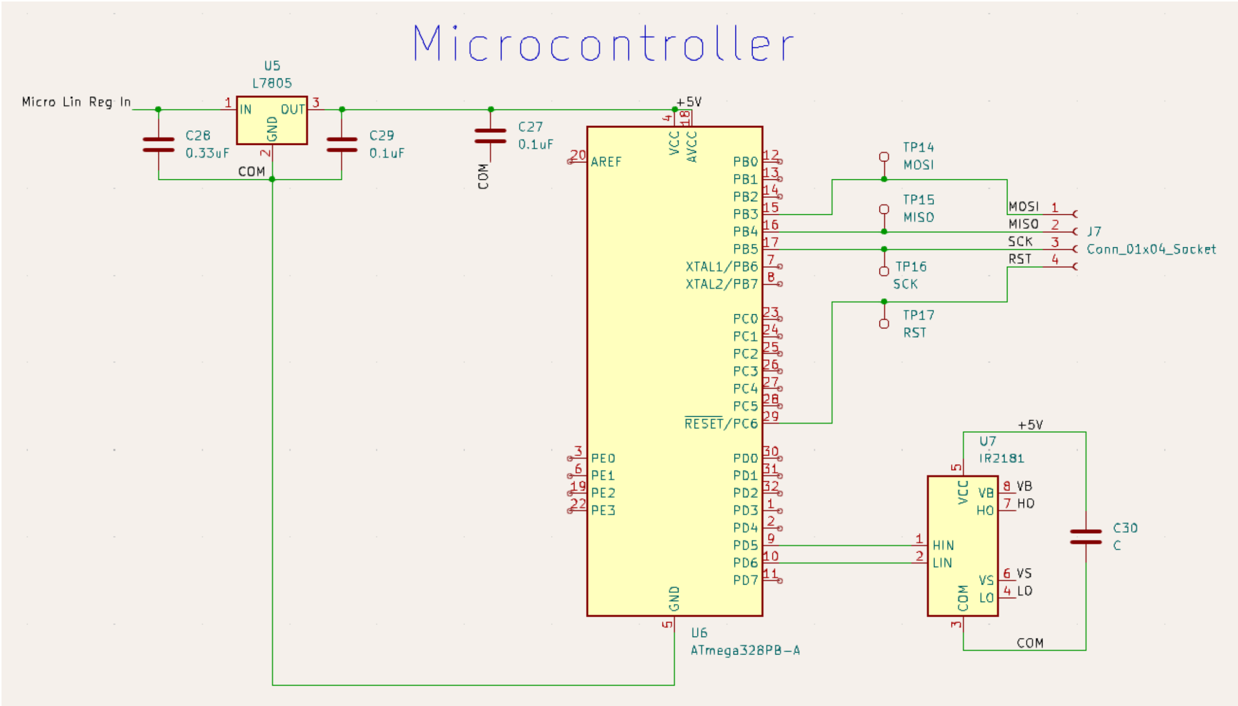

Figure 2.5 PCB schematic of Microcontroller subsection

Our design incorporates an ATMega328PB for the purpose of outputting a switching signal to the MOSFETs in our flyback converter. The ATMega and any associated chips at 5V, as shown in Figure 2.5, were all powered by a 5V linear regulator, as their collective current draw is quite low, providing little risk of overheating. We were able to use the ATMega's internal 8MHz clock to control Timer 1 and create a PWM output signal. Our final revision of the flyback simply required a 250kHz square wave signal with a 50% duty cycle. We were able to produce this wave by using the internal registers associated with Timer 1, outputting through pins PB1 and PB2. We opted to program the ATMega through SPI, after loading the bootloader using the method seen in Kakushin [4].

Due to the somewhat slow rising edge of the switching signal we opted to place a Schmitt trigger along the signal path to the switches. The Schmitt trigger acted both as a gate driver, and as a mechanism to sharpen the edges of our control signal, to maximize switching efficiency.

The ATMega328PB is a very powerful chip and in future revisions of this design could easily be utilized to incorporate more switching outputs, variable pulse width (which we did implement though not use in the final design), or signal monitoring to control a reactive switching cycle.

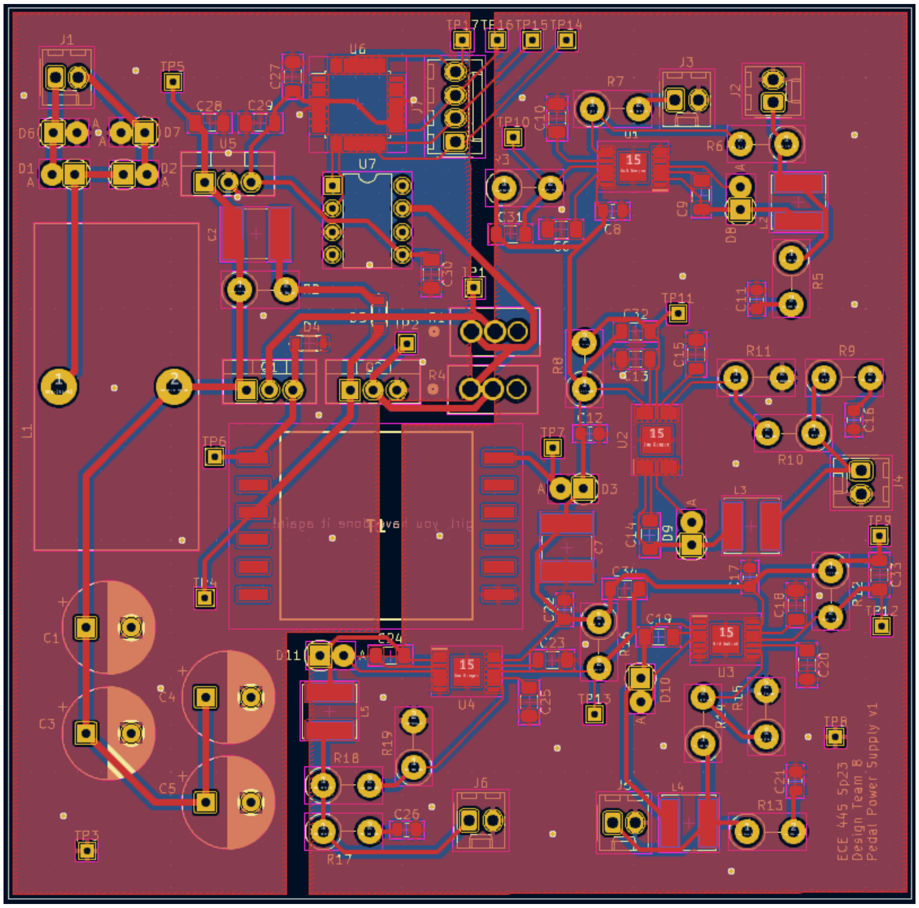

Figure 2.6 PCB Front

In the design of the PCB it was essential to consider truly separate grounding planes, and sufficient trace width to handle high voltage signals [5]. As can be seen in Figures 2.6 and 2.7, the ground plane connected to the primary coil of our DC/DC transformer is completely physically isolated from the ground plane of the secondary coil [6]. This physical separation allows the two grounds to be at different potentials and allow our transformer to function.

In future revisions of this board we might include test point access to even more signals, especially those connected to pins with particularly small profiles, as in the case of the microcontroller. The prototyping process could have been significantly sped up easy access to all these pins had been available, so that the software development would not need to be halted for quick revisions in soldering or tricky additions of completely new parts.

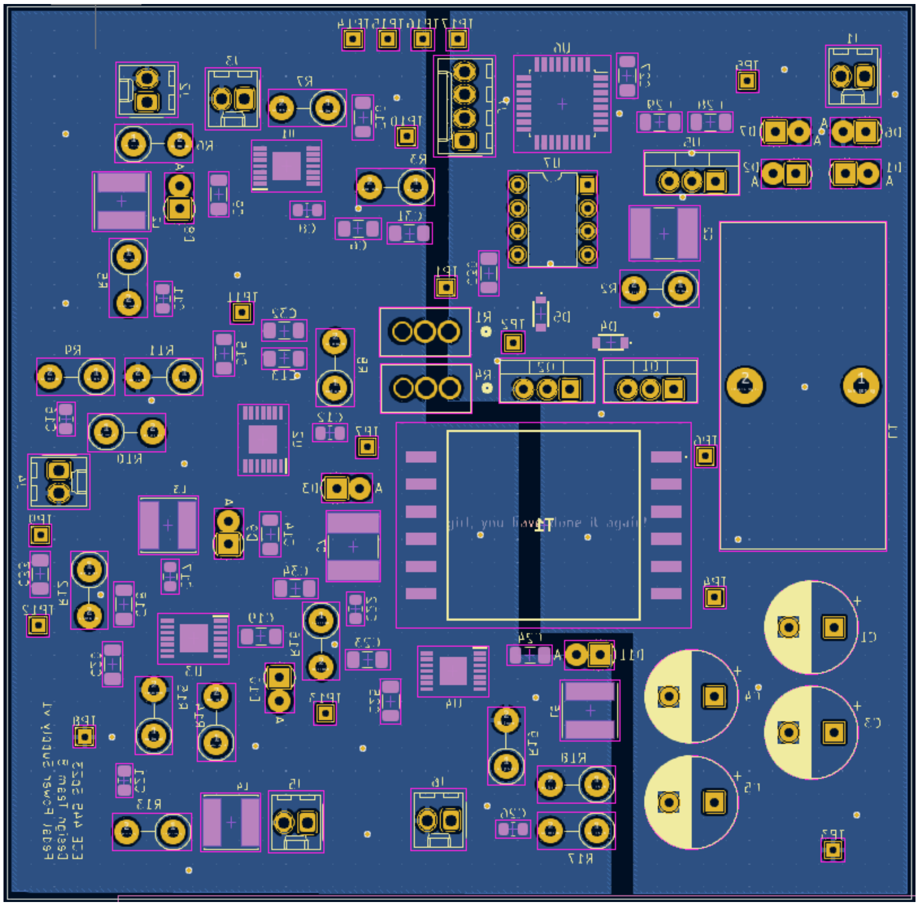

Figure 2.7 PCB Back

Verification

A large chunk of the testing process involved breadboarding different units in the system to make sure they worked on their own, then testing them connected to each other. A large emphasis was put on the AC/DC and initial DC/DC converters in breadboarding, trialing various configurations for particularly the DC/DC converter. Figures 2.8 and 2.9 show a flyback configuration, which was the ultimate configuration used for the PCB. Figure 2.8 shows the MOSFET switch gate signal for the DC/DC converter generated (top, yellow), and the output to the AC/DC rectifier when 60VAC is input (bottom, green). While there does seem to be some switching noise, it does overall obtain the flat signal we desire from a rectifier, with an output around 12.6VDC. Meanwhile, figure 2.9 shows the flyback converter in action, with the gate signal (top, yellow), and a 6.9VDC output signal (bottom, green) with a 12V input. While these two units separately worked successfully, we were unable to obtain the same results with the two units connected on the breadboard. This may be due to a variety of issues, not limited to switching noise interfering with the DC signal, and probing issues caused by non differential probes.

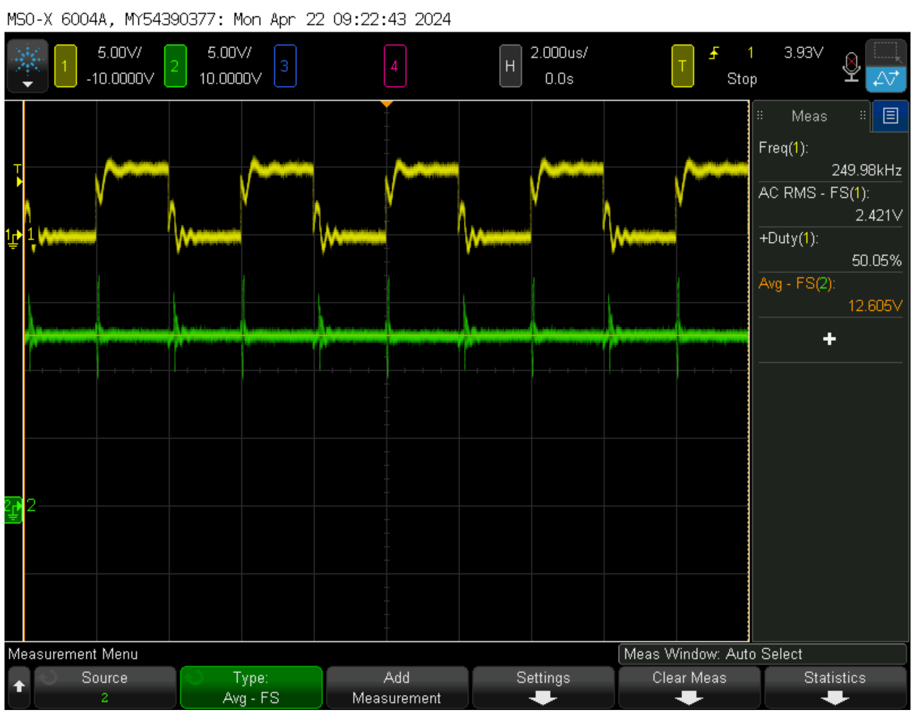

Figure 2.8 Rectifier output with 60VAC variac input

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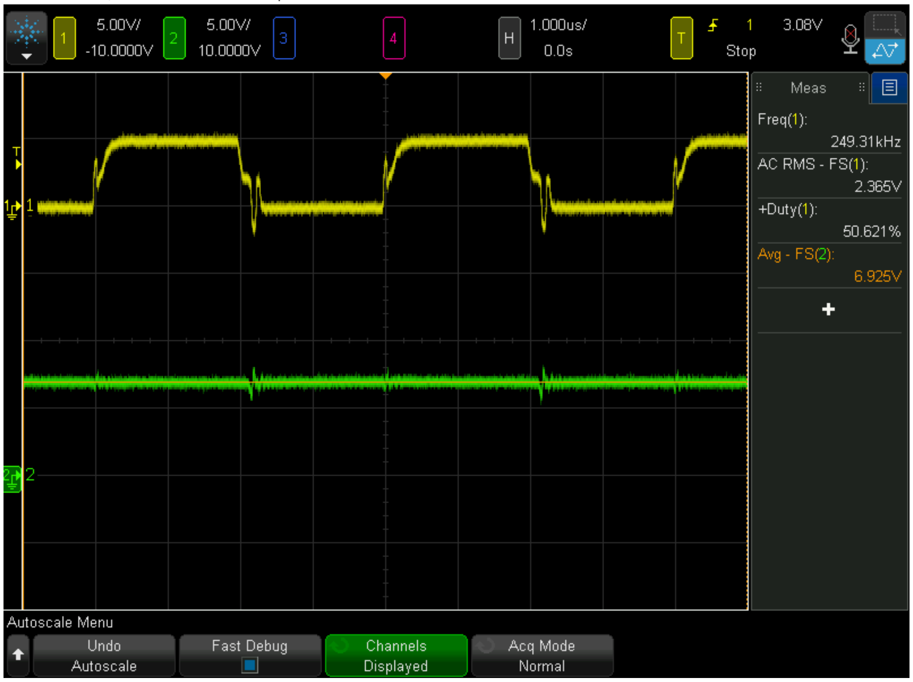

Figure 2.9 Flyback output (disconnected from rectifier) with 12VDC input

One configuration that was used during breadboard testing was the buck converter for the DC/DC converter. Figures 2.10 and 2.11 show the results from these trials. Figure 2.10 shows the rectifier output when the buck converter is connected, with a 60% duty cycle. We can see the gate signal on top in yellow and the rectifier output below in green. This shows less switching noise, and again a nice flat signal that is expected from a rectified DC output. Figure 2.11 shows the gate signal (top, yellow) and the buck converter output (bottom, green). As alluded to before, this configuration ended up working for our breadboard, and while it did output less switching noise, we ultimately determined that isolation was one of the core components in our project, and we could not abandon it, so we went forward with the flyback configuration in our final PCB, which produced fewer issues than its breadboarding counterpart.

Figure 2.12 summarizes our data from these breadboard tests. The AC/DC rectifier consistently outputs about a fifth of its input, which in our case yielded between 12-13V when input with 60V. For the flyback, our expected output was two thirds of the input. Given a 12V input, this should yield output 8V, and while our actual input was 1.1V lower than that at 6.9 volts, considering heating losses along the way, these are not completely out of the realm of our expectations. In the buck converter, we expected half of the input at the output. Which, given a 12V input, should yield 6V. Once again, we are below expectations by about 1.1V, but if we again consider heating losses, this is not too far off from our expectations.

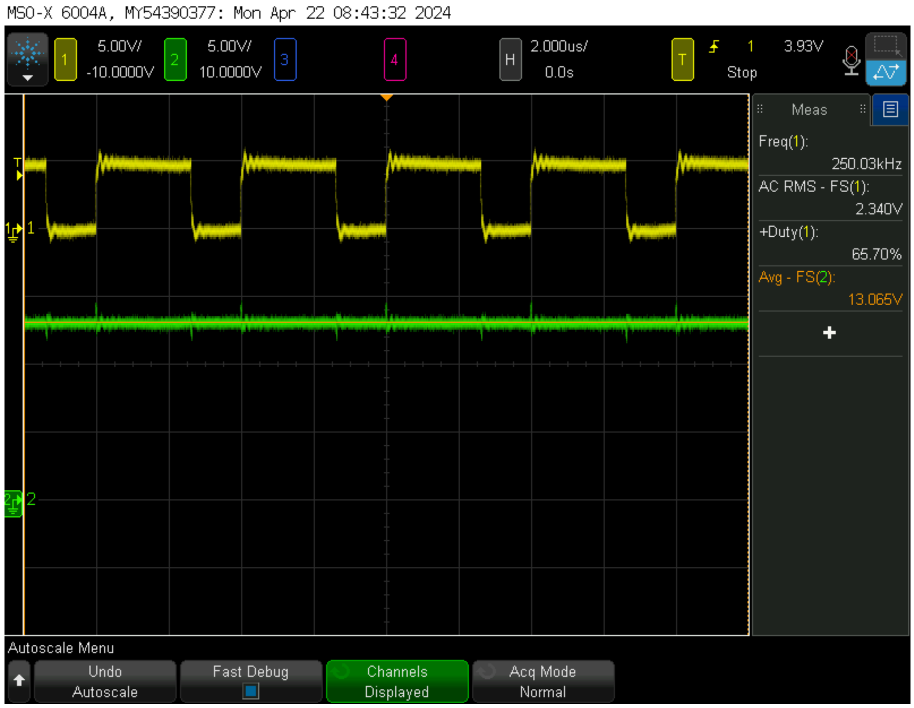

Figure 2.10 Rectifier output when connected to buck converter with 60VAC variac input

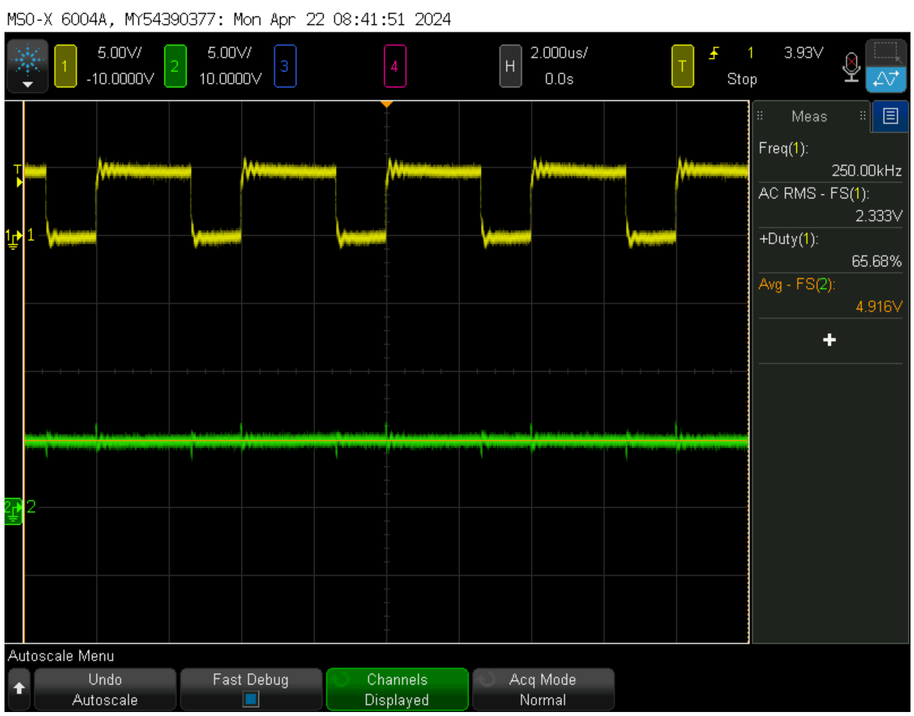

Figure 2.11 Rectifier to buck converter output with 60VAC variac input

	Variac input	Rectifier output		DC/DC input	DC/DC output	
		expected	*actual*		*expected*	*actual*
flyback	60 V	12 V	12.6 V	12 V	8 V	6.9 V
buck	60 V	12 V	13.1 V	13.1 V	6 V	4.9 V

Figure 2.12 DC/DC converter results

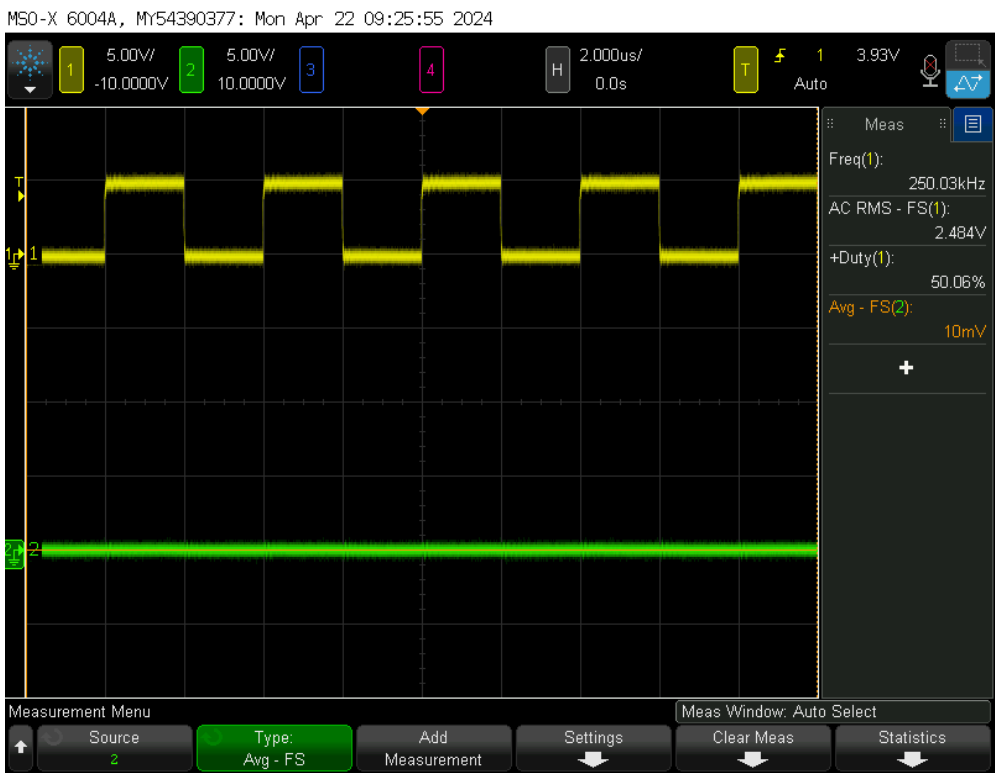

Figure 2.13 PWM signal display

As can be seen in Figure 2.13 the output from our microcontroller when not connected to any other parts of the circuit is a clean square wave signal between low logic level at 0V and high logic level around 5V DC. We determined qualitatively that the output signal's slope might require some additional sharpening, thus the addition of a Schmitt trigger between the microcontroller and the switches.

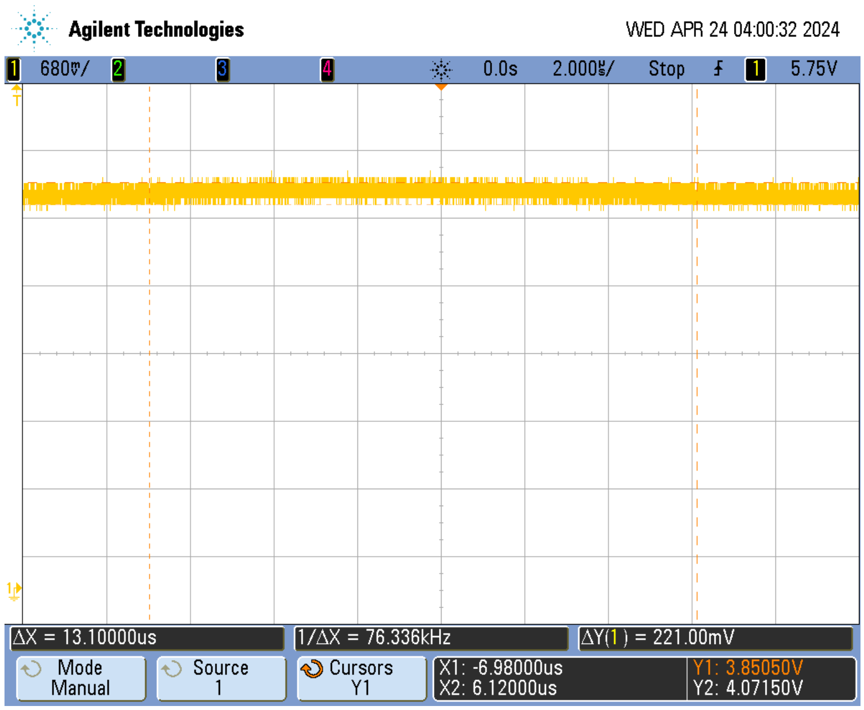

Figure 2.14 Example of ripple at output

While we were able to test the general buck converter schematic, we needed to do a controlled test on the buck ICs to verify they are able to properly step down the voltage. In order to do so we directly input a test voltage into the flyback output, which can be input into the buck converters. We used a 3kOhm load in order to dissipate the power put in the circuit. At the maximum voltage, the circuit drew a maximum of 14 mA. Despite setting the on time resistances as close to the calculated values as possible, the maximum voltages outputted were nowhere near the expected values, as seen in figure 2.15. Even adjusting these resistances did not affect the output voltages in a significant way. Given the buck ics operate with a series of set resistors and debouncing capacitors, the capacitance chosen may limit the power that could be passed through the converter. It may also be an issue with the loads being too large, causing the current draw to be so small and putting the bucks in discontinuous conduction mode. The resistors are set under this assumption the bucks are continuously conducting. If given more time, we would play around with the loads and capacitances in an attempt to raise the output voltages.

Output Port	Expected Output	Actual Output
9 V	9 V	3.5 V
12 V	12 V	6.3 V
15 V	15 V	7.5 V
18 V	18 V	5.7 V

Figure 2.15 Expected versus actual results of the buck ICs tested at a 24 V input

Once we verified the operation of the buck ics on the board itself, we attached the transformer and the variac to the rectifier input to verify the operation of the subsystems on the PCB itself. We were able to get an appropriate output from the rectifier, however even at a lower power the flyback did not get that high of an output. It took a full 120 volts of AC in order to produce 6 volts on the flyback output, which is the minimum voltage needed to get the bucks to produce a proper output. We managed to get the whole PCB fully producing an output once, at the expense of our flyback switch. The immense conduction losses likely played a role in why the flyback produced such a small output. The measured results at the DC/DC output can be seen in figure 2.16.

Output Port Being Measured	Expected Output	Measured Output
Flyback	24 V	~6.0 V
18 V Port	18 V	~5.4 V
15 V Port	15 V	~5.7 V
12 V Port	12 V	~4.8 V
9 V Port	9 V	~3.6 V

Figure 2.16 PCB DC/DC measurements when run at a full 120 AC Voltage

The underload portion of the circuit was also able to function as expected. It was able to react to user changes quickly and step down to voltage significantly. This is not surprising as it is simply a potentiometer the user can directly change the value of. Based on these results, we have not met many of the requirements outlined in our R&V tables in figures 2.17 and 2.18.

High-level Requirements

Requirement	Verification
Output ports supply expected DC voltage (+/- 3%) and output ripple of under 100 mV	Place the current probe of the oscilloscope in the current path of the output port and measure average and peak-to-peak amperage to make sure they are within the required values.
Undersupply "sag" output responds to user choice between 2V and 9V	Place the voltage probes of the oscilloscope between the 9V output port and ground and measure average and peak-to-peak voltage to make sure they are within the required values.
Response time for underload adjustment under one second	Use stopwatch and start when user switches from minimum to maximum voltage and stop once voltage level has stabilized at maximum.

Figure 2.17 R&V table for high level requirements

Subsystem requirements

Requirement	Verification
Current outputs for the output ports should not exceed 1A (but should stay in the ballpark of 500mA +/- 3%)	Place the current probe of the oscilloscope in the current path of the output port and measure average and peak-to-peak amperage to make sure they are within the required values.
Underloading DC/DC component should be adjustable anywhere 2 to 9V with minimum ripple across all possible voltages (+/- 3%)	Place the voltage probes of the oscilloscope between the output port and ground and measure average and peak-to-peak voltage to make sure they are within the required values.
For the non underloading DC/DC component we need it to output 4 voltage levels (9, 12, 15, 18) +/- 3% with a ripple under 100mV	Place the voltage probes of the oscilloscope between the output port and ground and measure average and peak-to-peak voltage to make sure they are within the required values.

Figure 2.18 R&V table for subsystem requirements

Cost Analysis

In?	component	part no.	quantity	cost / unit	total cost
yes	ATMega chip	ATMEGA328PB-AU-ND	1	$1.63	$1.63
yes	c14 jack		1	$8.34	$8.34
yes	output jack ports		1	$8.99	$8.99
yes	c13 cord		1	$6.86	$6.86
yes	output port to pedal cord		1	$10.99	$10.99
yes	DC-96P Heavy-Duty Electronics Enclosure		1	$19.44	$19.44
yes	gate driver	IR2181PBF-ND	1	$5.76	$5.76
yes	integrated bucks	LM25010-Q1	5	$2.91	$14.55
yes	linear potentiometer	026TB32R101B1A1	3	$5.36	$16.08
yes	5v linear regulator	L7805CV	3	$0.58	$1.74
yes	schottky diode	RB160M-40TR	10		$2.81
yes	dc/dc output inductor	VLS6045EX-221M	10	$0.36	$3.55
yes	ac/dc output inductor		3	$5.89	$17.67
yes	ac transformer		1	$33.36	$33.36
yes	dc/dc output inductor alternate	VLS6045EX-221M	1	$0.41	$0.41
yes	new MOSFETs	IRF540	1	$1.09	$1.09
yes	Buck ICs	LM25010-Q1	4	$2.91	$11.64
yes	Schmitt trigger	SN7414N	2	$2.84	$5.68
					TOTAL
					$170.59
	FREE PARTS				
yes	diode	1N4001			
yes	prewound flyback transformer	POE300F-24L			
yes	MOSFET	IRF100B202-ND / IRFI1310NPBF-ND			
yes	0.1 uF	[1206]			
yes	0.22uF	[0805]			
yes	10uF	[0805]			
yes	100uF (ceramic output)				
yes	ad/dc output caps				
yes	gate driver pots				
yes	ac/dc resistor				
yes	200k resistor				
yes	1K resistor				
yes	1.5k resistor				

Figure 3.1 Spreadsheet detailing part numbers and price breakdowns

Adding on to this an assumed wage of $30/hour, and an estimated 150 hours per group member, we can calculate the human labor costs for our group to be around:

$$\$30/hr \times 150hr \times 2.5 \times 3\,workers = \$33750$$

In addition, we were able to receive the services of the ECE Machine Shop. This simply involved drilling a few holes for user interface components into the provided plastic enclosure. We can thus calculate the labor cost for their work:

$$\$30/hr \times 2hr \times 2.5 \times 1\,worker = \$150$$

Conclusions

While we did not obtain the exact results planned from the beginning, we were able to verify proof of concept in our design, by successfully stepping down from wall power, rectifying, stepping down again, and providing two stages of isolation. Our DC outputs remained quite stable while powered, though their voltage values were incorrect. Each output provided a separate line of power, and was able to supply significant current to an external load. For the sag output in particular we were able to achieve change in output voltage in a negligible amount of time by changing the overall design of the circuit.

In a future implementation of this project we would plan to begin by breadboarding our design at full power, in a laboratory setting with access to accurate current probes, and differential voltage measurements. Our early lack of access to these tools may have contributed to compensations in unnecessary areas of the design. These tools would additionally allow us to have accurate readings without risk of current or voltage spikes because of ground discrepancies between our isolated system and an external earth connection. It would also be advantageous to include some current limiting and monitoring devices to our design. In practical application, we would intend for our design to be as resilient to current spiking as possible, to protect the fragile audio equipment it is designed to be used with. For future breadboarding we would include more test points and broken out connections for pins on all parts, but particularly the microcontroller. Having quick and easy access to signals from all pins could speed up the development process significantly by reducing time spent accessing floating connections.

Following the IEEE Code of Ethics [7] we believe our project does not provide any greater ethical concerns than any common household low voltage power supply. While there may be ethical concerns in sourcing our materials, these are more high level ethical concerns that are not specific to this project. The project itself is only meant to be a tool to help power, and is not meant to breach privacy or harm anyone, physically or otherwise. In terms of safety, while the project does deal with power, this is relatively low power, and thus creates only a low risk of danger of electric shock or heat issues. We have also taken measures in the production of our project's housing to minimize any possible points of contact between a user and any electrical connections. All jacks are standard and pose little risk of accidental contact.

Regardless of our difficulties, we were able to address a great number of shortcomings of our designs through extensive troubleshooting. From testing alternative topologies on an external breadboard such as alternate flyback converter configurations, we were able to successfully rule out various issues that may have completely ruined our whole system and make it unsafe for users. We were also able to make quick changes when parts behaved differently than our expectation, as in the case of replacing our gate driver with a schmitt trigger.

While the end product of our team's project was not exactly ready for the market, with some work, we do hold the belief that it could be a useful device. Furthermore, there may be elements we could add to enhance the utility and safety of our product once the issues that occurred during testing are resolved. These could include fuses, to prevent any current surges from injuring anyone, as well as the option to run the device off of a battery instead of a wall outlet, for ease of portability. Although our project isn't going to change the world, our focus on isolation may be a valuable asset to musicians who, just like our engineering team, are always seeking to perfect their craft.

Appendix

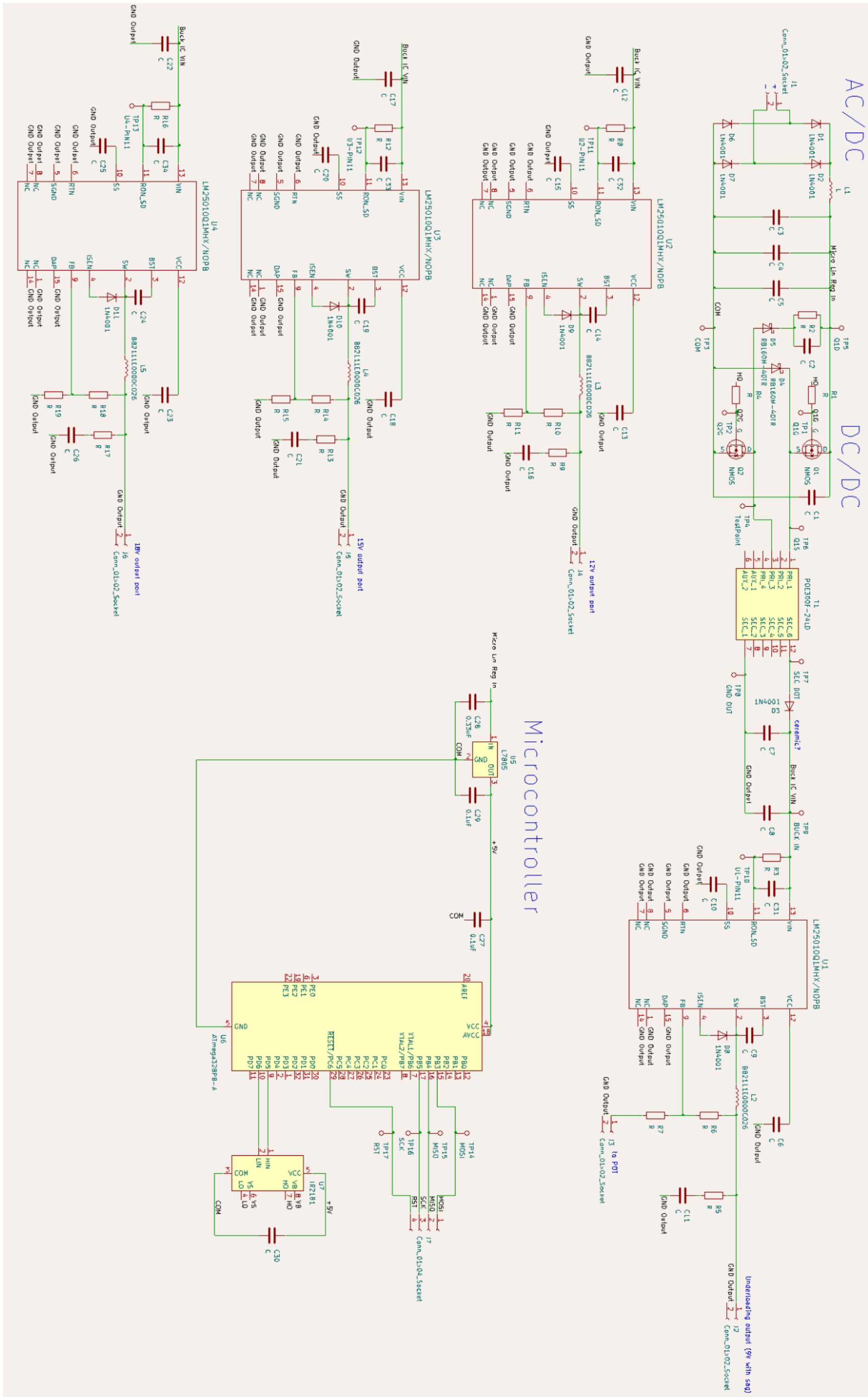

Figure 4.1 Full Schematic View

References

[1] "MXR® ISO-BRICKTM POWER SUPPLY," Dunlop. https://www.jimdunlop.com/mxr-iso-brick-power-supply/ (accessed Mar 21, 2024).

[2] "Pedal Power® 2 PLUS – Voodoo Lab," *voodoolab.com*. https://voodoolab.com/product/pedal-power-2-plus/ (accessed Mar 20, 2024).

[3] "Repairing a Voodoo Labs ISO 5," Voodoo Labs Youtube. https://www.youtube.com/watch?app=desktop&v=qPRMe6wE1h8 (accessed May 02, 2024).

[4] "Bootloader and upload to Atmega328P-AU," Kakushin Youtube. https://www.youtube.com/watch?v=VVK0aYcrnQc (accessed Apr 10, 2024).

[5] S. Lovati, "High-Power PCB Design," Power Electronics News, Feb. 04, 2021. https://www.powerelectronicsnews.com/high-power-pcb-design/

[6] "How to Connect Grounds in an Isolated Power Supply PCB Layout," Altium, Aug. 23, 2021. https://resources.altium.com/p/how-connect-grounds-isolated-power-supply-pcb-layout/

[7] IEEE, "IEEE Code of Ethics," ieee.org, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html