Master Thesis

Czech Technical University in Prague

F3

Faculty of Electrical Engineering
Department of Measurement

Guitar amplifier design

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Supervisor: Prof. Ing. Jan Holub, Ph.D.
Field of study: Electrical engineering
Subfield: Cybernetics and robotics
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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Cybernetics and Robotics**

II. Master's thesis details

Master's thesis title in English:

Guitar amplifier design

Master's thesis title in Czech:

Návrh kytarového zesilovače

Guidelines:

Design and implement a guitar amplifier consisting of the following parts:
1. Preamplifier with adjustable distortion, equalization, overall volume and reverb effect (use FV-1 sound processor)
2. 40W class-D end amplifier with THD+N max. 1%

The design will include the development of the PCB and mechanical design to a fully usable state for user and/or production. Verify the achieved prameters by measurements. Compare the achieved THD and the catalogue data of the components used.

Bibliography / sources:

1. online documentation for the FV-1 (Spin Semiconductor - Audio measurements on the FV-1)
2. Popovich I.S., Audio Tests & Measurements, Career Professionals, 2019, 0980622395, 9780980622393
3. Pohlman C.K., Principles of Digital Audio, McGraw Hill, 978-0071663465

Name and workplace of master's thesis supervisor:

prof. Ing. Jan Holub, Ph.D. Department of Measurement FEE

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **26.09.2023** Deadline for master's thesis submission: **09.01.2024**

Assignment valid until:
by the end of winter semester 2024/2025

prof. Ing. Jan Holub, Ph.D. Supervisor's signature	Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt	Student's signature

Acknowledgements

I want to thank my supervisor Prof. Ing. Jan Holub, Ph.D. for his time and help with my thesis. Another thanks belongs to Antonín Salva for consultations and advice about the project and David Karon for supplying me with the necessary materials. My biggest thanks however belong to my family, my girlfriend, and my friends for their help, patience, and neverending support over my studies.

Declaration

I hereby declare that I have worked on this thesis independently and specified all the used information sources in accordance with the Methodical guidelines about following ethical principles during the preparation of university theses.

In Prague, 1. January 2024

Abstract

The thesis deals with the complete design of a guitar amplifier to the point of a finished device aimed at an end user. From choosing the requirements of the finished device, selecting the individual important building blocks, putting together the final schematic, and dividing the design into individual PCBs, their design, and the mechanical chassis design in which the electronics are placed. The device is powered by a 24VDC/60W adapter and the amplifier produces 40W power on the output using the TPA3106D1 chip from Texas Instruments. The preamplifier allows the user to amplify and distort the signal, three-band equalizer, mix control of a digital reverb effect (reverb of the FV-1 audio processor with adjustable parameters by inside trimmers), master volume setting and a vacuum tube ECC83 section (powered by 120V voltage multiplier). The tube section is designed in a way that it can be left out of the device so that the device can drain as low power as possible.

The document contains also a measurements section where the power of the individual parts is measured, also the frequency characteristics of the equalizer, and the datasheet THD value of the power amplifier's TPA3106D1 is verified.

Keywords: Guitar amplifier, preamplifier, power amplifier, TPA3106D1, class-D amplifier, THD, vacuum tubes, voltage multiplier, FV-1, digital reverb effect, PCB design

Supervisor: Prof. Ing. Jan Holub, Ph.D.

Abstrakt

Práce se zabývá kompletním návrhem kytarového zesilovače do stavu dokončeného zařízení určeného pro koncového uživatele. Od výběru požadavků výsledného zařízení, přes výběr jednotlivých důležitých stavebních bloků, sestavení výsledného celkového schématu, rozdělení návrhu do jednotlivých plošných spojů, jejich návrhu a návrhu mechanické konstrukce ve kterém jsou umístěny. Zařízení je napájeno 24VDC/60W adaptérem a zesilovač produkuje 40W výstupního výkonu využitím čipu TPA3106D1 od společnosti Texas Instruments. Předzesilovač umožňuje zesílit a zkreslit signál, obsahuje 3-pásmové korekce, nastavení přimíchání digitálního efektu dozvuku (reverbu z audioprocesoru FV-1 s nastavitelnými parametry vnitřními trimry), nastavení celkové hlasitosti a sekci s vakuovou elektronkou ECC83 (napájenou 120V napěťovou násobičkou). Elektronková sekce je navržena tak, aby se dala jednoduše vynechat z konstrukce a zařízení tak odebíralo co možná minimální výkon.

Dokument obsahuje také měření příkonů jednotlivých částí zesilovače, přenosové frekvenční charakteristiky navržených korekcí a změřeno a ověřeno celkové harmonické zkreslení koncového zesilovače podle dokumentace.

Klíčová slova: Kytarový zesilovač, předzesilovač, koncový zesilovač, TPA3106D1, class-D zesilovač, THD, vakuové elektronky, napěťová násobička, FV-1, digitální reverb efekt, návrh PCB

Překlad názvu: Návrh kytarového zesilovače

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Part I

Introduction and research

Chapter 1

Introduction

Figure 1.1: Photo of the finished amplifier.

Guitar amplifier design is an engineering discipline of developing an amplification device for musicians to use with a wide range of features and possibilities. The development is rather subjective, selection of the electronics building blocks, selecting the user controls, the frequency bandwidths for equalizers, etc. With the electronics development going on, the possibilities for these designs are expanding every day. Therefore I decided to design an amplifier that combines current new components and building blocks namely designing a modern high-efficiency power amplifier enabling high power with low power consumption and signal distortion.
In this project, we design an amplifier from scratch to a point of fully functional reliable device prepared for the end user. We set up a list of requirements and limitations and developed the amplifier around it. From the user's functional perspective, the amplifier will deliver controls of Gain, Bass, Middle, Treble,

Reverb, Master volume, bypassable tube stage (with high cathode voltage), effects loop, a guitar input, and speaker output. The plan is to select functional blocks to deliver these control options, design the complete schematics, the PCBs, and the mechanical chassis enclosure which will sit in a wooden shell to properly mechanically protect the device, test the device, and measure key parameters of the device. Mainly measure the power consumption of the complete amplifier, the frequency spectrum of the three-band equalizer, and the THD of the power amplifier. The power amplifier will be a class-D amplifier that delivers high-efficiency amplification with very low THD, the measurement aims to confirm or disprove the information from the datasheet.

Chapter 2

Research

2.1 Guitar amplifier

Figure 2.1: MARSHALL 2002 JCM 900.[1]

A guitar amplifier is an electrical device that is designed to shape and amplify a guitar signal to reproduce sound waves through a loudspeaker(s). Their development begins in the early 1920s to give guitarists a loud enough sound to cut through the mix of a band with louder instruments such as drums or horns. Typically developed from radio amplifiers, they quickly became a big part of musicians' way of music interpretation. They are typically designed in two options, independent guitar amplifier head with loudspeaker output to be connected to a reprobox via external cable (see figure 2.1) or a guitar combo that combines these two devices into one box. Each option has its pros and cons, the amplifier head being more versatile (range of easy amp and loudspeaker options) and the combo being more practical and also

a typically cheaper option. There is a wide range of options being produced from small 1W combo amplifiers (for example Marshall DSL1CR[10]) aimed as a home use practice amplifiers to 100W amplifiers designed to produce loud enough sound for medium-sized concerts (for example MARSHALL 2002 JCM 900, see on figure 2.1).[11, 12]
From an electronic perspective, guitar amplifiers are mono amplifiers with high input impedance and low output impedance (loudspeakers are typically 4/8/16Ω impedance) that are either directly pluggable into the wall with an integrated power source inside (power transformer) or with a power adapter. Their purpose is to shape the signal to the user's taste. For example, it is expected that the amp will be able to distort and compress the signal, shape the frequency spectrum, set the output level, and optionally simulate room response as a reverb with all of these attributes adjustable by the user with potentiometers. This is typically achieved by separating the device into two blocks - The preamplifier and the power amplifier. The preamplifier's purpose is to take care of the sound shaping. The power amplifier amplifies the signal from the preamp to a power output high enough for the loudspeaker to reproduce into acoustic waves. Between these two blocks, there is usually an option to connect external effect units via the Effects loop.[11, 12]

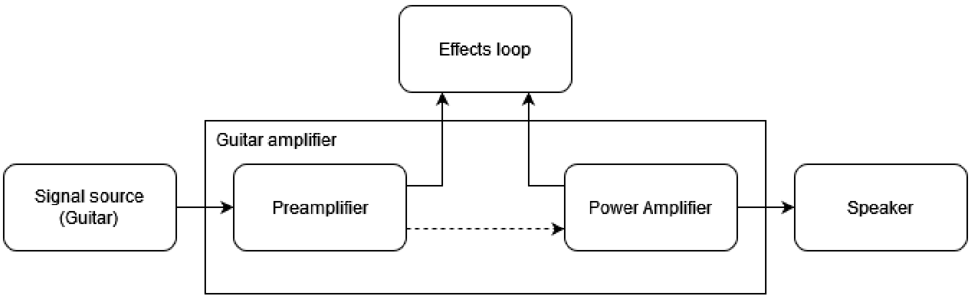


Figure 2.2: Basic block diagram of guitar amplifier.

With development starting in the 1920s no surprise that the early amps were designed with vacuum tubes. Most of the current market's standards are based around these designs that continued mostly in the 1960s to 1980s but are still being developed nowadays. Transistor amps are also very common but not very popular in the high-end market. Because of this, we can separate guitar amps into a few groups.[13, 14]

2.1.1 Vacuum tube amplifiers

Guitar-based popular music was experiencing a huge expansion in the 1960s and 1970s as well as guitar amp and overall electronics design development. Being more and more in demand several iconic guitar amps were being developed and since it was in the 70s, the most popular active component for guitar amp design was the vacuum tubes which became most popular and common. Even to this day, all-tube amplifiers are still the most preferred amp designs in many cases. Their pros are simple circuit design, high output power, and easy modifications. Their most prominent advantage is probably their typical frequency characteristics and natural high harmonics distortion.[15] Their cons are high price (due to mostly hand-wired and assembled THT design and the high price of the tubes and output transformers), the overall weight of the device (caused by the transformers), the need for a high voltage and low power efficiency (disabling options of neglecting power transformers and using adapter-like DC power sources). A typical example is Marshall JCM 900 see in figure 2.1.[16, 14, 17, 18, 13]

2.1.2 Solid-state amplifiers

Solid-state amplifier states for transistor-based guitar amplifier design. Their pros are low price, low THD of the power amplifier, low overall weight, high reliability, and high power efficiency. Despite their pros, most musicians still prefer the natural harmonic distortion caused by their tube amp equivalents.[13, 12, 19, 11]

2.1.3 Hybrid amplifiers

Hybrid amplifiers combine the two options above. Typically having a transistor power amp for the clean power amplification and a tube preamp for the frequency response and preferred harmonic distortion. This allows for avoiding the output transformer with sufficient power output. Another alternative is to feed a tube power amplifier with a transistor-based preamplifier which enables the simple high output power property of the tube power amp.[14, 17, 18, 15, 13]

2.1.4 Modelling amplifiers

The development of digital technology enabled to inclusion of digital sound processing into the guitar amplifier design. It allows the use of onboard simulation of a wide range of sound effects and tones such as different room responses (reverbs), modulation effects, and different speaker cabinet simulations. These are called modeling amplifiers and can even simulate characteristic tones of different existing amplifiers. Their development vastly expanded during the last two decades and is getting more and more popular even in the high-end market. The most widespread high-end modeling amplifier currently is the KEMPER Profiler which is used for studio sessions but also for live playing (see figure 2.3).[12]

Figure 2.3: KEMPER Profiler modeling amp.[2]

Part II

Schematic, PCB and mechanical construction design

Chapter 3

Design preparation

The topic of this thesis is Guitar amplifier design and after a short introduction to the problematics of the current amplifier designs, I decided to design an amplifier that combines the different amplifier groups, taking the pros of each group. My design will be powered by a 24VDC/60W power source with a transistor class-D power amplifier, transistor preamplifier with bypassable tube stage, and digital reverb (room response simulation).
Guitar amplifiers are very versatile and they differ in design. There is no exact ideal amplifier or parameters to chase for the development. The selection of parameters is therefore very subjective and needs to be chosen by the designer's taste. For this reason, many choices and selections in the following amplifier design section cannot be explained to the last point.

3.1 Basic requirements

The main project requirement is to design the device into a form of robust fully working unit, ready for potential production, including housing for the electronics and the outside visuals. By that, it is meant for the electronics to fit into a metal chassis which will be placed into a wooden shell.

3.1.1 Power

The goal of this project is to avoid heavy and expensive power transformers and to make the device DC-powered by an adapter, similar to what is used for laptops with power consumption below 3A.

3.1.2 Connectors

For an easy user-friendly amp design, it is required to use market standard connectors, for signals 6.3mm audio jack connectors, for power supply 2.1mm shaft DC jack connector. DC jack connector and phono jacks for the speaker and effects loop will be placed on the back panel of the device.

3.1.3 Circuit section selection

The preamp will contain two special sections. First a bypassable vacuum tube section, second space response emulation of Reverb. Both are sections preferred to be designed as modules so that they can be replaceable for example tube section with another OP amp gain section or being missed out totally to lower the overall power consumption and reverb with some kind of one-knob modulation (chorus, vibrato, etc.).

3.1.4 User controls

As for user controls, I decided to have this set of controls:

- Power switch - turns the amp off totally or to low-power mode
- Gain - controls gain of the first OP amp gain section
- Tube bypass switch - bypass the tube section circuit
- Bass - controls the cut/boost of bass frequencies
- Mid - controls the cut/boost of mid frequencies

- Treble - controls the cut/boost of treble frequencies
- Reverb - controls the amount of reverb in the signal
- Master volume - controls the overall output volume of the preamp section

These controls will be placed on the front panel of the chassis.

3.2 Block diagram design

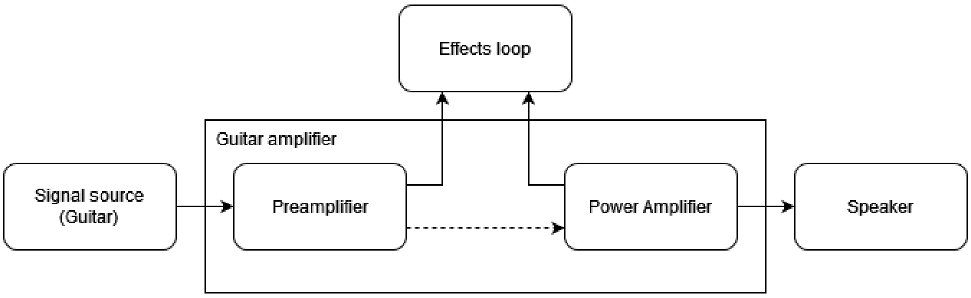


Figure 3.1: Generic guitar amp block diagram

This project follows a standard guitar amp design diagram that separates the circuit into preamp and power amp with effects loop in between (see figure 3.1 and 2.2).

Chapter 4

Power distribution, protection and effects loop design

4.1 Power protection

To protect the circuit from malfunctioning it was necessary to design power protection for the device. The schematic can be seen in figure 4.1. The fuse $F1$ protects the circuit in case of some inside shortage leading to high current being drawn, the diode D8 1N5406 protects the circuit from the reverse voltage source and the diode D9 BZW06-33B protects the circuit against overvoltage. The capacitor C100 is there only to smooth out the DC voltage source and to help power the circuit in high-power drain spikes.

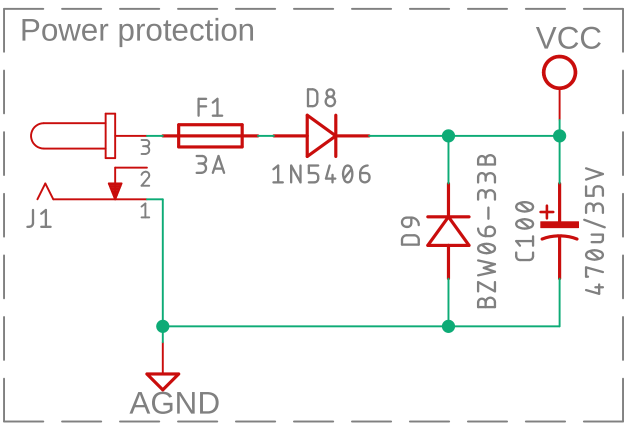


Figure 4.1: Power protection schematic.

4.2 Power distribution

This project was decided to be powered by a standard 24VDC 60W power source. The power amp is going to be powered directly by the 24VDC voltage, the preamplifier will be powered by an 18V regulator (to separate voltage sources of the power amp and preamplifier to minimize the noise generated by the pulse power consumption characteristic of the class-D power amplifier). The tube stage will be powered by a 12V regulator directly from the 24V power source for the heaters (to lower the current output of the preamplifier's 18V regulator) and with its power solution for the anode powered by the preamplifier's 18V regulator. The reverb stage's analog part of the circuit will be powered by the preamplifier's 18V regulator and the FV-1 with its 3V3 regulator powered by the 18V. See on block diagram in figure 4.2.

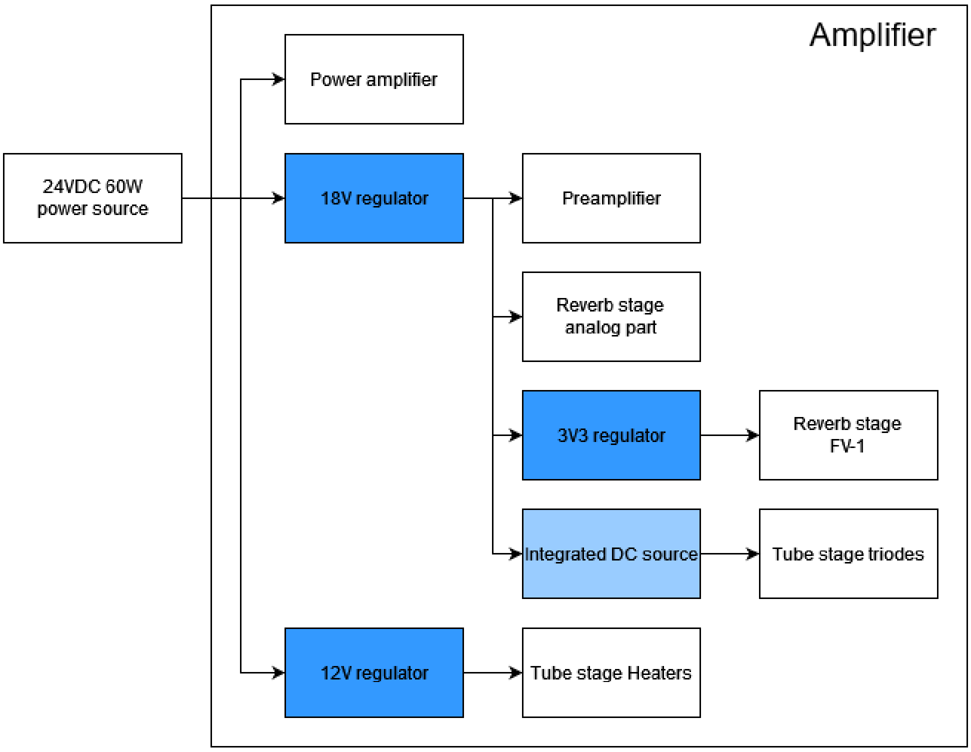


Figure 4.2: Amplifier power distribution diagram.

4.3 Effects loop

The effects loop is an alternative signal path between the preamplifier and the power amplifier. The effects loop section allows the user to use external signal processing devices outside the amplifier between the preamplifier and power amplifier. It is required to be connected when unused and send and return the signal when the cable is plugged in. The schematic can be seen in figure 4.3. The 6-pin phono jacks offer an easy solution since they contain a set of contact pins that are shorted when cables are unplugged and unconnected when the cable is inserted.

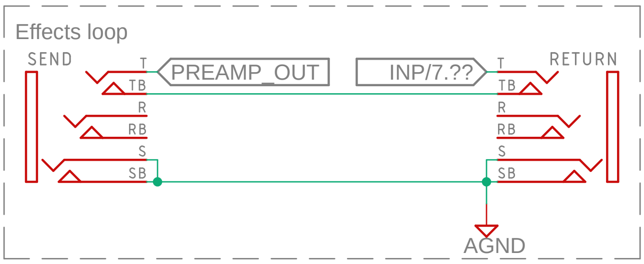


Figure 4.3: Effects loop schematic.

Chapter 5

Preamplifier design

For the preamp, I selected functional blocks as shown in figure 5.1. The general idea of this design is to amplify the signal to a high enough level to be usable for the musician after it gets through the final power amplification and the speaker and to deliver sound shaping options including equalization, gain, reverb, and master volume.

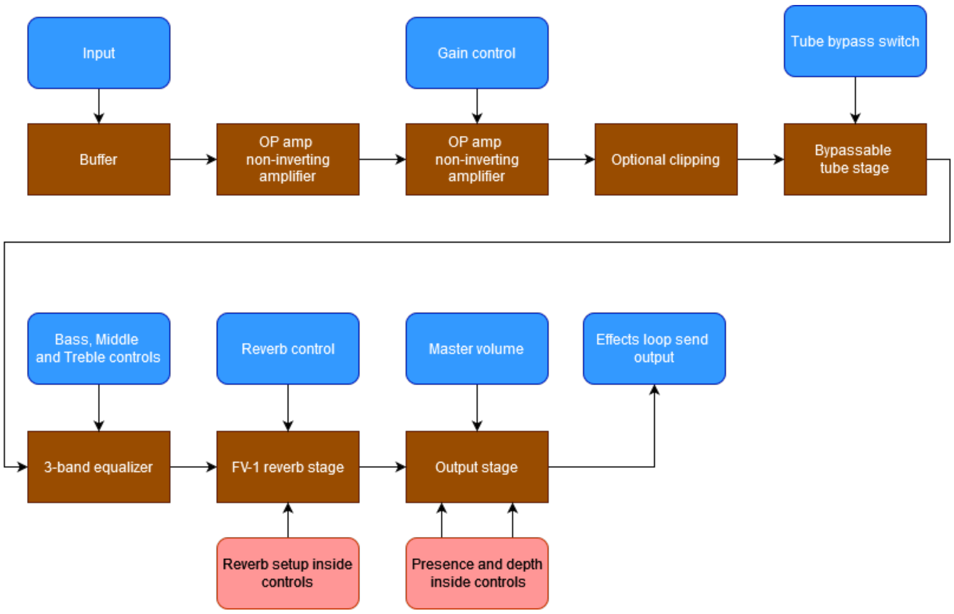


Figure 5.1: Preamplifier block diagram.

5.1 Voltage regulator for the preamplifier and main on/off toggle switch

The power amplifier of this project is a class-D power amplifier. This means that to achieve the efficiency of the amplification it consumes the power in short pulses. This creates a noise on the power rails that would get amplified in the preamplifier. For this reason, it is necessary to separate the preamplifier's power from the power amplifier with a voltage regulator. The output voltage of the regulator needs to be significant enough to cancel out the noise on the power rails but at the same time not to exceed the need for an external heatsink. For this reason, I chose an 18V regulator which should be low enough voltage and also with maximum estimated $I_{preamplifier} = 500mA$ current draw produces up to $P_{reg} = I_{preamplifier} \cdot U_{drop} = 3W$ external heat which is sufficient to cool with integrated copper plate heatsink of the PCB layers.
The ON/OFF switch is required to put the device into power-saving mode with as low a current draw as possible. The preamplifier is estimated to draw a very low current, approximately around $200mA$ so the main power consumption comes from the power amplifier which is then required to shut down. The used TPA3106D1 power amplifier chip includes an SDZ shutdown pin which does just that and also makes the switching ON/OFF noiseless. To turn off the power amplifier the pin SDZ needs to be simply grounded. When the device is on the indication LED turns on as its cathode gets grounded with the required current-limiting resistor.
The schematic of the Preamplifier's voltage regulator and the ON/OFF switch can be seen in figure 5.2 below.

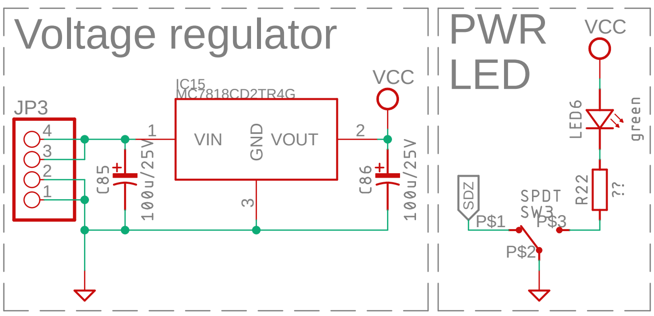


Figure 5.2: Preamplifier's voltage regulator and the ON/OFF switch.

5.2 Input buffer and OP amp amplification stages

The signal needs to be strong enough to get clipped by the optional clipping stage and the bypassable tube stage. Controlling the gain then controls the overall distortion created. To achieve this I chose a Jfet buffer (voltage follower) which delivers high input impedance and low output impedance. There is also a resistor $R1 = 1M\Omega$ which takes care of voltage spikes on the input and lowers potential clicks on the signal when for example true bypass with a strong mechanical switch is turned on in front of the amp. [11]

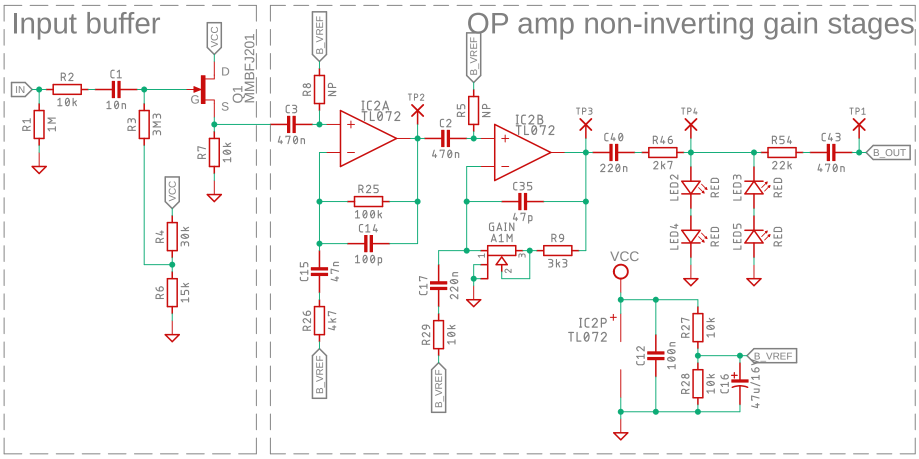


Figure 5.3: Input buffer and OP amp gain stages schematic.

The two OP amp gain stages are set not to change the frequency characteristics of the signal and the overall gain to amplify the signal so that it does not get clipped by the OP amp due to its 18V power limitations. The signal on the input can vary based on the signal chain in front of the amp which can consist of some boosters or any different devices which amplify the signal. To avoid clipping the signal by the OP amps which is overall not very desirable by musicians, I added an optional clipping stage consisting of LED2, LED3, LED4, and LED5 which clips the signal before the OP amps of the rest of the preamplifier with smoother curve (based on the volt-amper characteristics of the LEDs) then the OP amp power clipping. The overall gain varies based on the user setup of the Gain potentiometer and equals to:

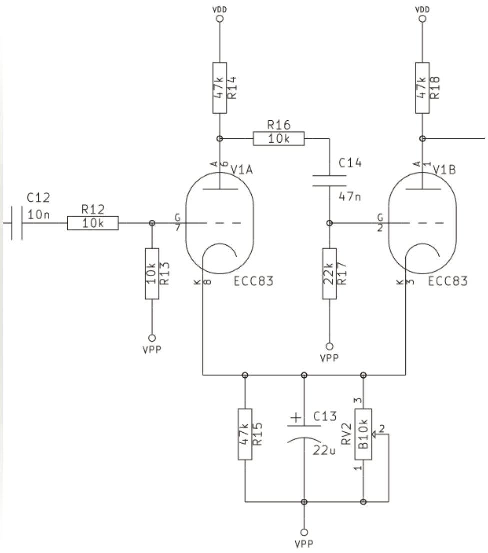
$$\begin{aligned} G_{min} &= G_{first\ stage} \cdot G_{second\ stage,min} \\ &= \left(1 + \frac{100000}{4700}\right) \cdot \left(1 + \frac{3300}{10000}\right) = 22.27 \cdot 1.33 \doteq 30.19 \end{aligned} \tag{5.2.0.1}$$

$$\begin{aligned} G_{max} &= G_{first\ stage} \cdot G_{second\ stage,max} \\ &= \left(1 + \frac{100000}{4700}\right) \cdot \left(1 + \frac{3300 + 1000000}{10000}\right) = 22.27 \cdot 100.33 \doteq 2256,61 \end{aligned} \tag{5.2.0.2}$$

5.3 Bypassable tube stage

The tube stage was designed based on two available open-source projects Tube Driver V1.2 from TH Custom Effects and TUBE DRIVER kit ULTRA from Guitar-Electronics.eu (emulating famous BK Butler tube driver see on figure 5.4b). From them, I chose the analog signal path of the tube stage part of the BK Butler Tube Driver kit and the voltage multiplier from the Tube Driver V1.2.[20, 3]

(a) : B.K. Butler tube driver. [21]



(b) : TUBE DRIVER kit ULTRA schematic.[20]

I assembled and tested the TUBE DRIVER kit ULTRA as a proof of concept prototype and figured that typical vacuum tube triodes start to pass the signal from $24V\,DC$ anode to cathode voltage but since the typical operational voltage of these components is around $300V\,DC$ it was desired to design the power section to produce as high DC voltage as possible with as low amount of components as possible. In the Tube Driver V1.2 schematic (see figure 5.5) we can see that they used a voltage multiplier with 40106N Schmidt trigger chips. This is possible since the tubes need this high voltage only as a voltage operational reference and it takes a very low current to run these (with $100k\Omega$ they drain at $120V$ around $1.2mA$). The $9V$ DC source they use produces around $60V$ (as they refer to in their documentation). In the article Designer's Notebook we can see that we can also use $18V$ power supply for these and that it almost doubles the output voltage (see figure 5.6). The output current of the power source is limited by the current output of the Schmidt trigger blocks and as the Designer's notebook it can be increased by stacking the blocks in parallel which based on their pinout is quite an easy

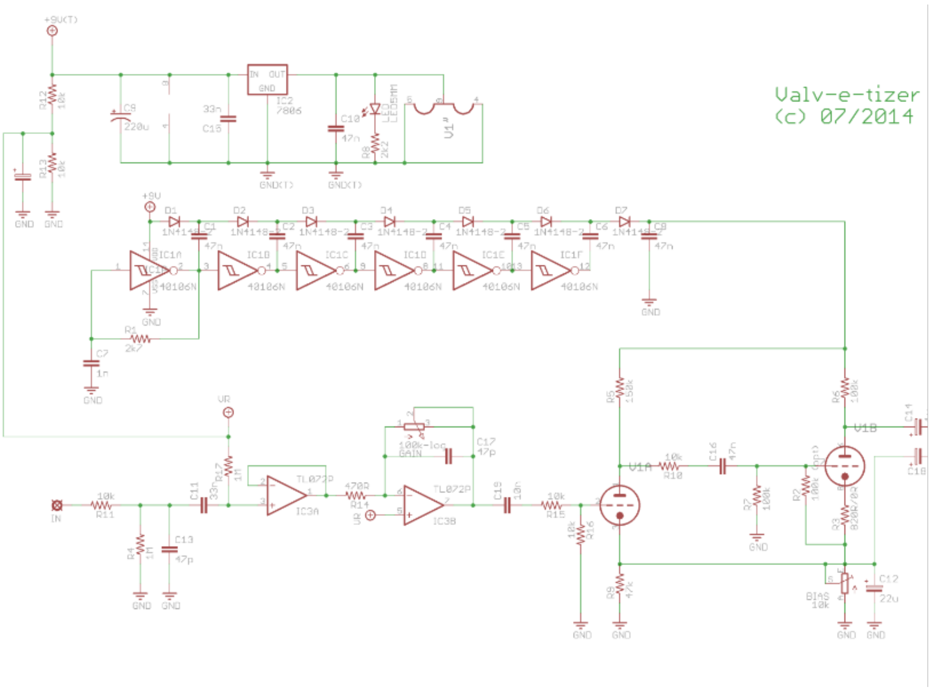


Figure 5.5: Tube Driver V1.2 schematic.[3]

and effective solution. I decided to use the same amount of multiplying stages as in the BK Butler Tube Driver kit since the component usually goes with 6 integrated blocks which will give us three stages (running two in parallel) and I will use two chips.[3, 4, 20, 18]

TABLE 1

	CMOS SUPPLY VOLTAGE					
	5V		10V		18V	
OUTPUT POLARITY / NO. OF STAGES	+	−	+	−	+	−
1	8.6	3.6	18.6	8.6	34.6	16.6
2	12.9	7.9	27.9	17.9	51.9	33.9
3	17.2	12.2	37.2	27.2	69.2	51.2
4	21.5	16.5	46.5	36.5	86.5	68.5
5	25.8	20.8	55.8	45.8	103.8	85.8
6	30.1	25.1	65.1	55.1	121.1	103.1
7	34.4	29.4	74.4	64.4	138.4	120.4

Table relating supply voltage and number of stages to the (unloaded) output voltage, for positive and negative output multipliers based on the circuits of Figs. 3a and 3b and allowing 0V7 for each diode drop.

Figure 5.6: Voltage multiplier table of supply voltage and output voltage relation.[4]

To lower the output current of the preamplifier's 18V regulator I separated the power for heaters and connected it directly from the back PCB's 24VDC power source. This can be done since it is assumed that this does not produce noise to the signal path and is even commonly powered by AC voltage. The two projects above use either 6VDC voltage for the heaters or 12VAC. I decided to go with 12VDC to lower the voltage drop on the regulator to avoid the need for a heatsink. It is also a popular solution for this kind of tube application in modern amplifiers.

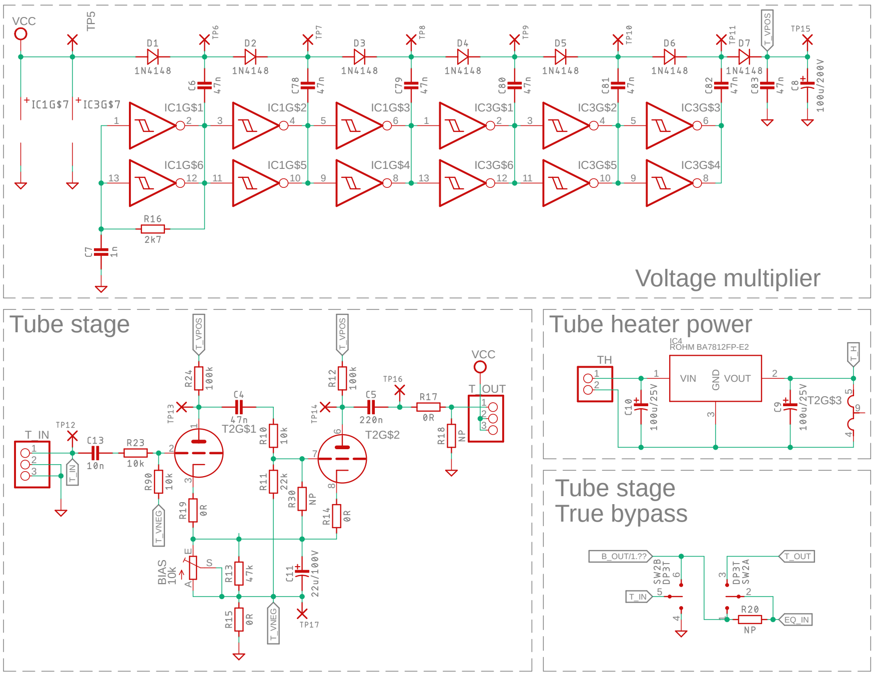
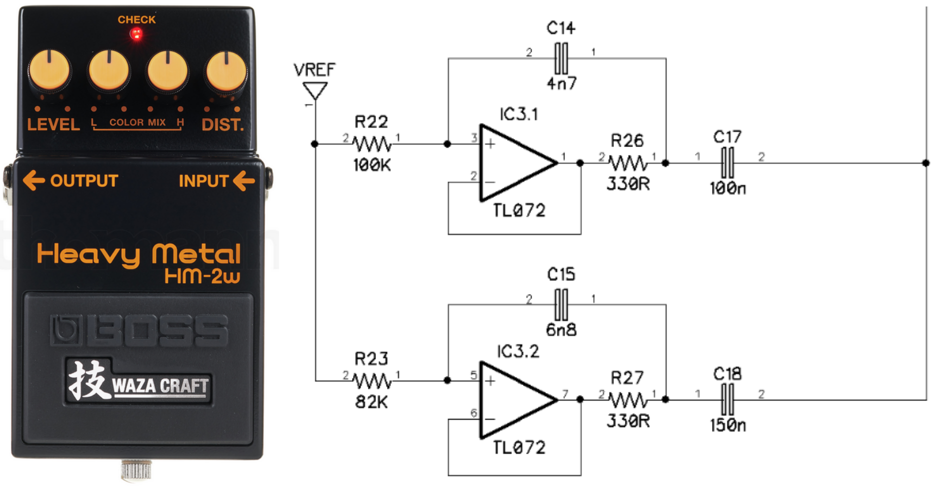


Figure 5.7: Tube stage schematic.

For testing purposes and more use flexibility (enabling an easy option of missing out on the tube stage and lowering the overall power consumption of the amplifier), I decided to make this stage bypassable. This will be achieved as a true bypass situation with a DPDT toggle switch. The wiring is in figure 5.7. This solution not only bypasses the stage with a true metallic signal (true bypass) path but also mutes the input of the tube stage when not engaged. This is crucial since the tube stage is designed with a high gain and if there is some noise on floating input it would get amplified and potentially transferred to the rest of the circuit as noise. The resistor R20 allows jumping the necessary connection in case the preamplifier is desired to be assembled without the tube stage. The complete schematics can be seen in figure 5.7.

5.4 Three-band equalizer



(a) : Boss HM-2W [22]. **(b) :** Promethium Distortion high bandwidth schematic [23].

Figure 5.8: Boss HM-2W and its emulated EQ section.

For the equalizer, I decided on active equalization which means it will be made out of active components being able to cut and boost the chosen frequency bandwidths. The main reason for this is the Mid-bandwidth. The two most typical frequency characteristics for guitar tones are either Mid boost or Mid scoop. These are used in different situations based on the musician's selection. Active EQ naturally allows this option very easily since as been said they deliver cut and boost options. The mid bandwidth was inspired by the bandwidth in the very popular and famous pedal Boss HM-2W (see figure 5.8a). The circuit comes from PedalPCB's open-source project Promethium Distortion [23] which emulates the Boss HM-2W. Even tho the bandwidth in this project is labeled as high (see figure 5.8b), it is very usable and popular as a Mid-frequency bandwidth. The circuit is built with two individual blocks for each bandwidth (around $1kHz$ and $1.3kHz$), each with a gyrator that creates with the rest of the components a typical bandwidth

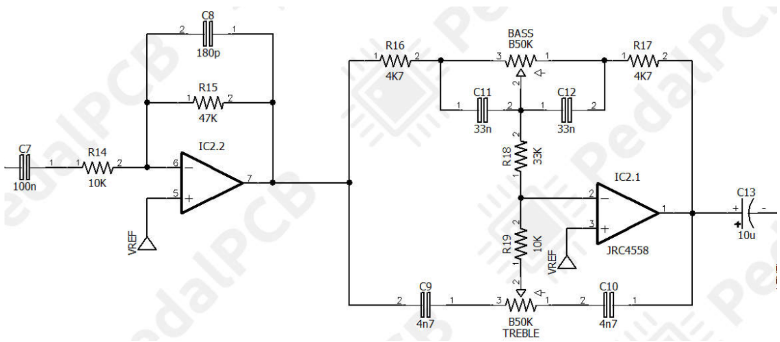


Figure 5.9: XB-MB Preamp EQ section schematic.[5]

RLC circuit.
The Bass and Treble part of the EQ is based on PedalPCB's open-source project XB-MB Preamp's EQ section (see figure 5.9). The complete schematic of the three-band EQ is in figure 5.10.

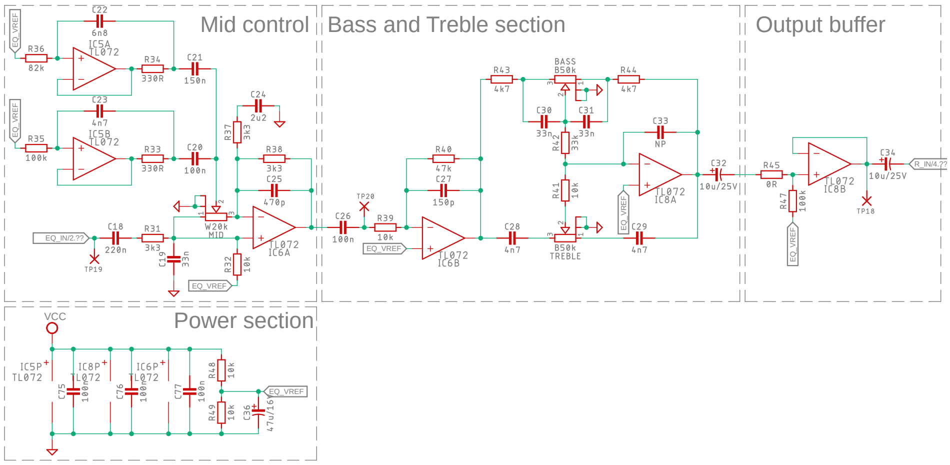


Figure 5.10: Three band EQ schematic.

5.5 FV-1 Reverb stage

The reverb stage was built around the FV-1 audio processor from Spin Semiconductor. The FV-1 provides an all-in-one solution for several audio effects with the need for only a simple circuit to complete the signal path. Signal in this stage gets separated into two parallel signal paths. The dry signal goes to the output unchanged and the wet signal is created by the audio processor and is mixed with the dry signal on the output. To make this happen it is necessary to start with an input buffer that allows the separation of the signal into two without any signal loss, the dry signal then continues to another buffer (labeled as a dry buffer) to avoid the feedback of the wet signal back to the signal processing and then into output mix. The wet signal goes after the input buffer into a reverb effect control functioning as a simple voltage resistor divider and into the FV-1 audio processor circuit block. After the signal processing the left and right channels get mixed and go into a buffer to flatten the output impedance before the output mix. The output mix is an inverting amplifier that amplifies and mixes the signal based on values of $R72$, $R73$, and $R74$ which are set to the gain of $G_{mix,1} = -1$ for both signal paths but can be easily modified. The inverting amplifier also flips the phase of the signals so to avoid mixing problems with signals out of

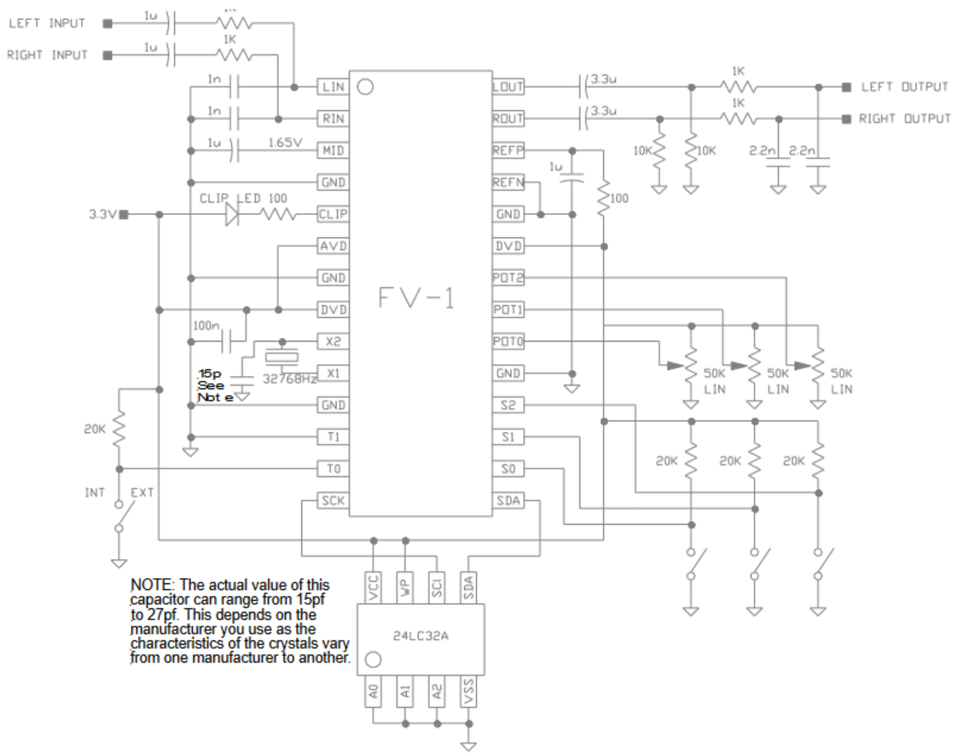


Figure 5.11: FV-1 typical application schematic. [6]

phase there is another inverting amplifier with $G_{mix,2} = -1$.[24, 6]
The FV-1 effect core is created from the typical application circuit from the FV-1 datasheet (see figure 5.11). For this application, I chose the signal volume control of the wet path Reverb as the user-control potentiometer and decided to use the additional FV-1 POT0, POT1, and POT2 as an internal trimmer. For the program, I chose the pre-programmed Reverb that is integrated into the chip under the last memory slot, therefore set the S0, S1, and S2 to high. The complete schematic can be seen in figure 5.12.[24, 6]

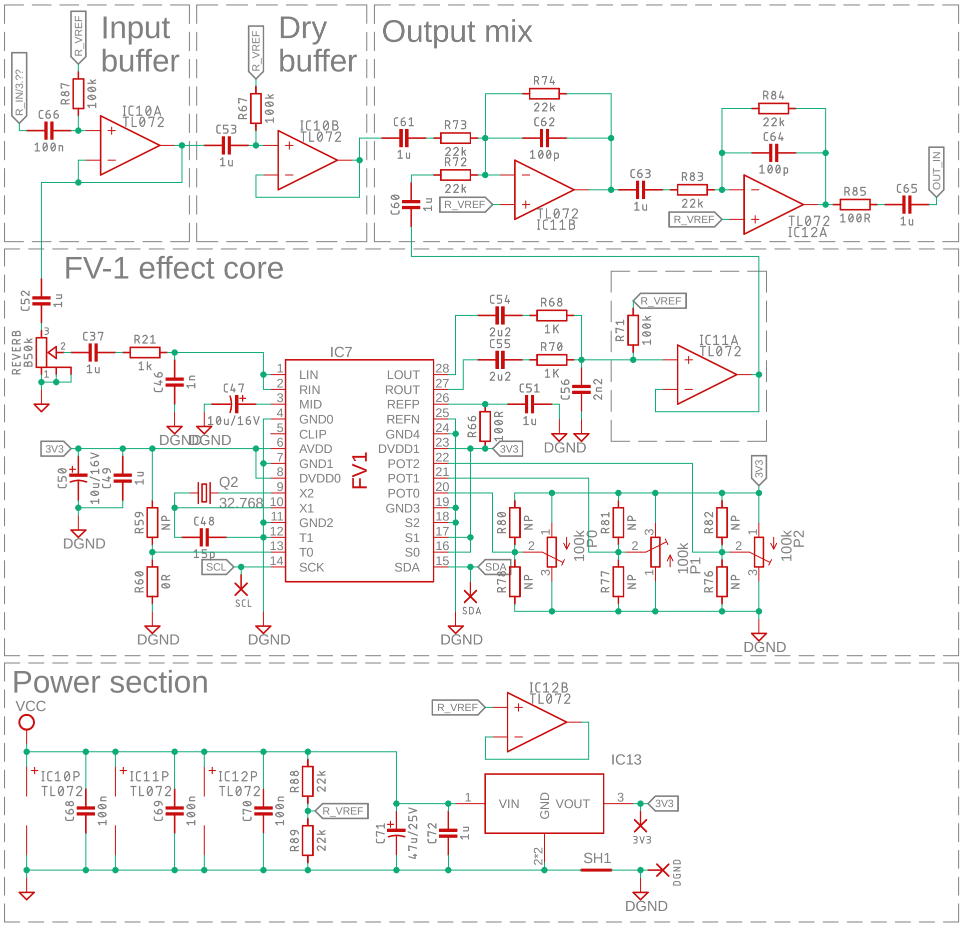


Figure 5.12: The FV-1 reverb section schematic.

5.6 Output stage

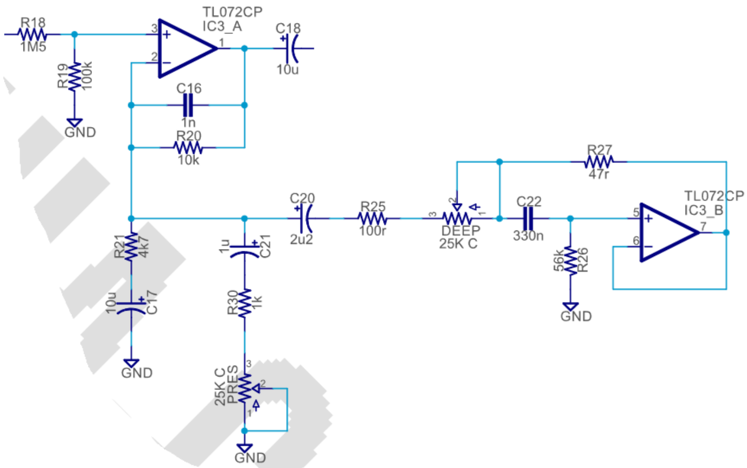


Figure 5.13: Benzin VH4 output section schematic. [7]

The output stage takes care of the overall output volume and impedance. For this block, I chose an output block of the PCB guitar mania's open-source project Benzin VH4 kit, see figure 5.13. The Benzin VH4 is powered by a symmetrical supply generated by a charge pump. Therefore the design is modified to an asymmetrical supply with virtual ground created by $R75$ and $R86$ resistors voltage divider. The Benzin VH4 block also contains two additional equalizations typical for guitar amplifiers, Presence (which boosts the upper mid-range frequencies) and Depth (which boosts low frequencies). These equalizations are not usually looked at as on standard equalizer since these came up with tube amplifiers which often offered these controls as part of the power amp. For this reason, they are placed in the preamplifier as close as possible to the power amp. [7, 25]
The complete schematic of the output stage can be seen in figure 5.14.

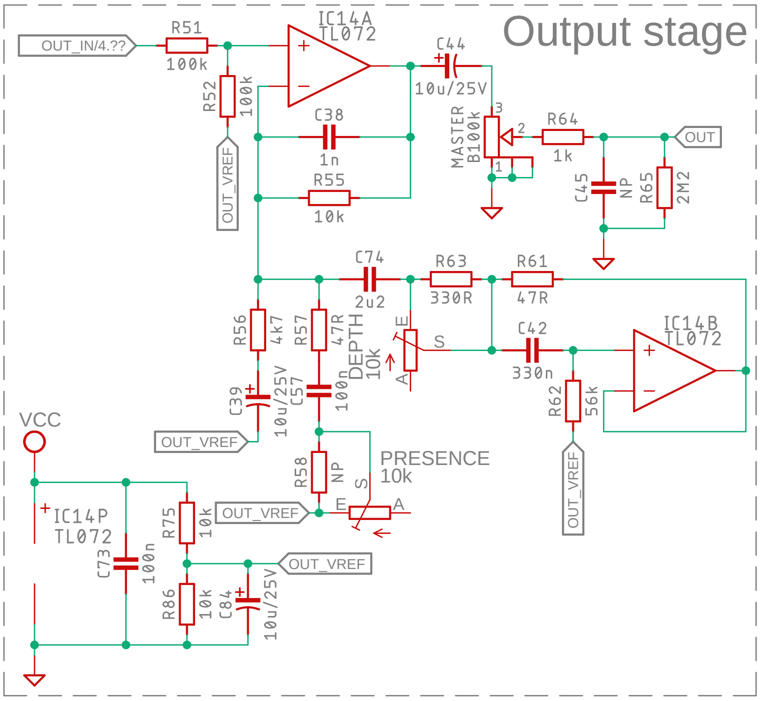


Figure 5.14: Schematic of the preamplifier's output stage.

Chapter 6

Power amplifier

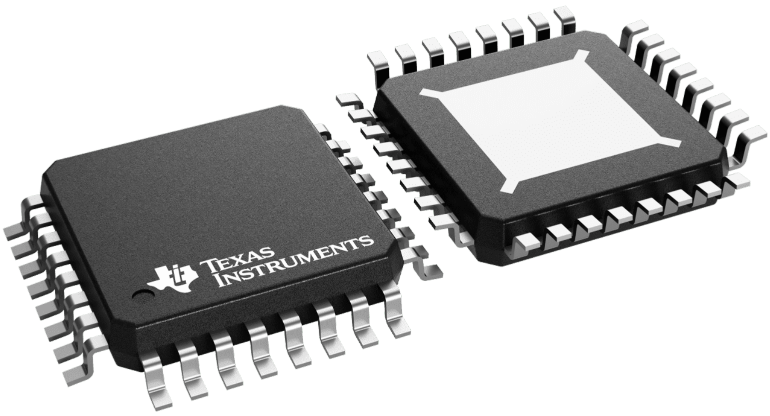


Figure 6.1: FV-1 typical application schematic. [8]

For the power amplifier, I chose TPA3106D1VFPR from Texas Instruments. This chip provides a 40W mono class-D amplifier. It can be powered by a DC voltage power supply ranging from $10V$ to $26V$ which is sufficient for the $24V\,DC$ power source used for this project. The TPA3106D1 processor is a high-efficiency class-D amplifier that neglects the use of a heater and the heat dissipation then transfers into the PCB making it a simple solution for this application. The minimal load is set as 4Ω which works for this application since most of the guitar speakers are 8Ω or 16Ω.[8, 9, 19, 26, 27]

Texas Instruments also offers an open-source example project TPA3106D1EVM - TPA3106D1 Evaluation Module with schematic and PCB manuals. This project includes a very specific schematic including component type information and voltage specifications for the amplifier design. The power amplifier schematic for this project was based on this schematic.[8, 9]

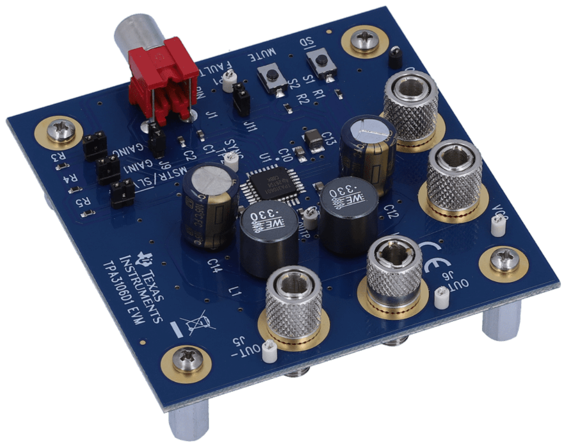


Figure 6.2: TPA3106D1EVM - TPA3106D1 Evaluation Module.[9]

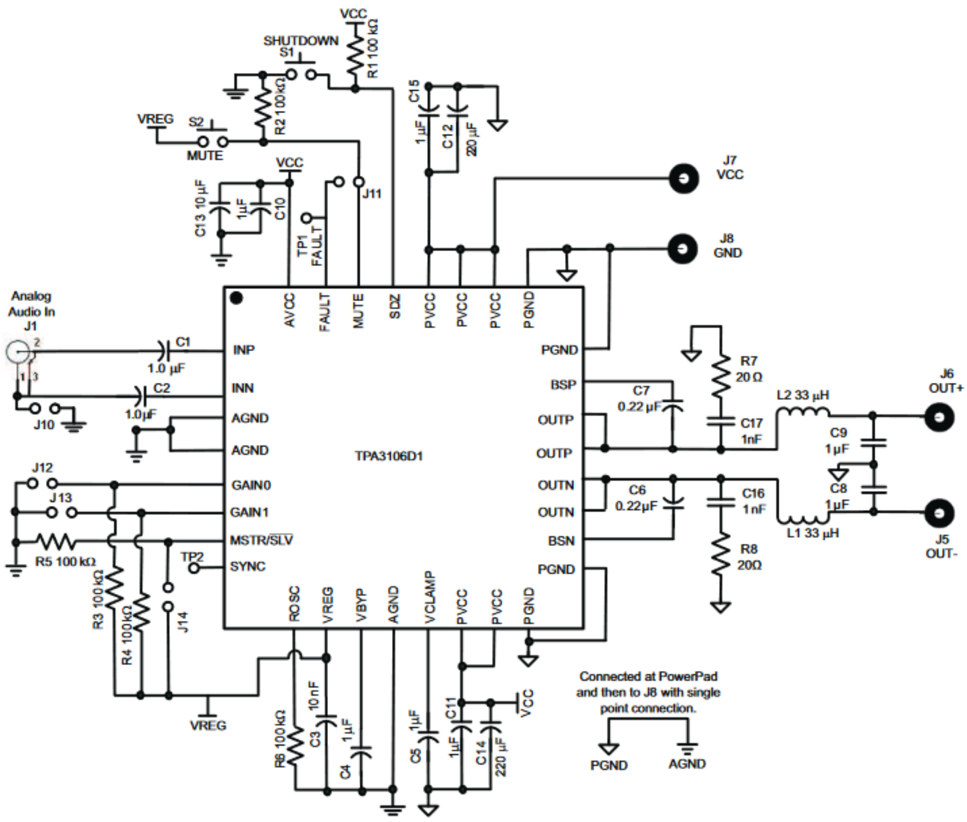


Figure 6.3: TPA3106D1EVM - TPA3106D1 Evaluation Module schematic.[9]

The complete schematic is on the schematic on figure 6.4 below. The amplifier can be turned off with an SDZ (shutdown) pin which turns off the amplifier when grounded. The shutdown mode minimizes the power consumption and has a silent switch to ON state. TPA3106D1 can drain up to $2A$ current in peaks so there are four pins as VCC for the $24VDC$ and five PGND pins. There is power ground and signal analog ground separated and connected by a short as advised in the TPA3106D1 datasheet and evaluation board. The TPA3106D1 offers four different gain options that can be selected by the $JG0$ and $JG1$ jumpers or can be fixed by $R95$ or $R96$ with 0Ω resistor.[8]

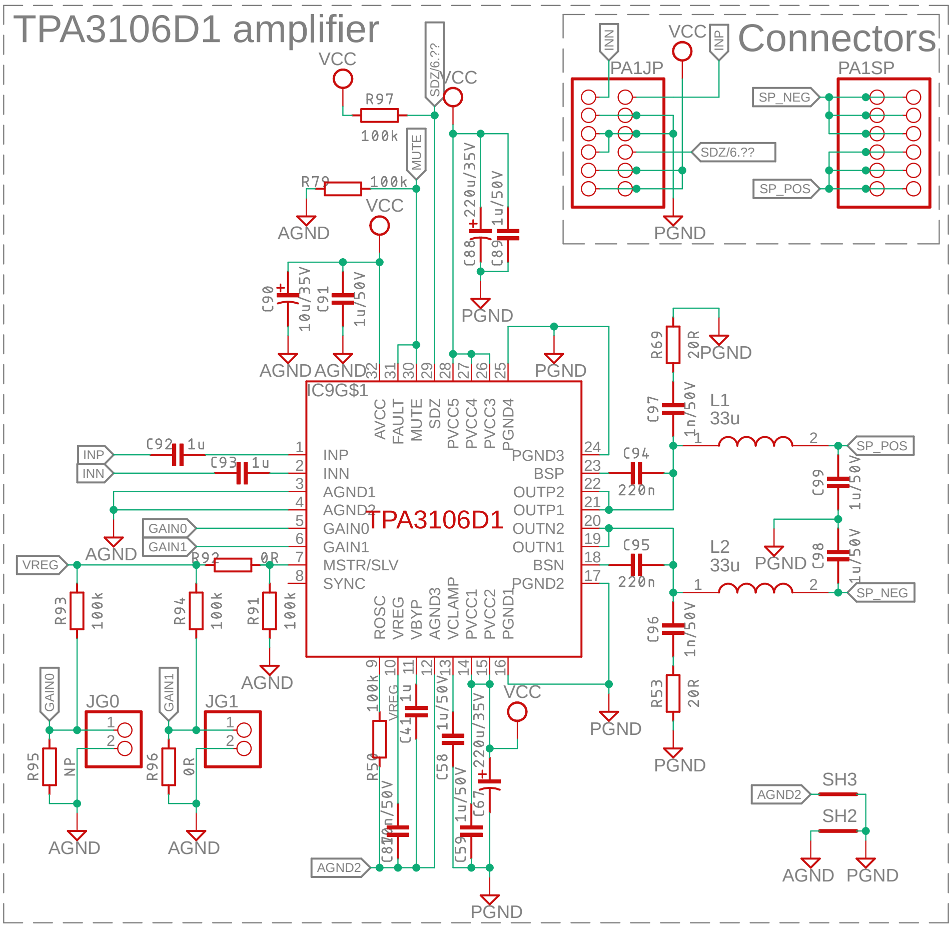


Figure 6.4: Schematic of the preamplifier's output stage.

Chapter 7

PCB and mechanical design

The PCBs are designed in Autodesk Eagle v9.6.2 and all 3D models of boards, chassis are designed in Autodesk Fusion 360.

7.1 Chassis enclosure

Figure 7.1: Photo of the wooden tolex-coated shell.

The guitar amplifier project is aimed to fit into a wooden tolex-coated shell of dimensions 305x160x160mm. The wooden shell is designed for a metal chassis to fit inside with dimensions 225x128x45mm mounted with screws

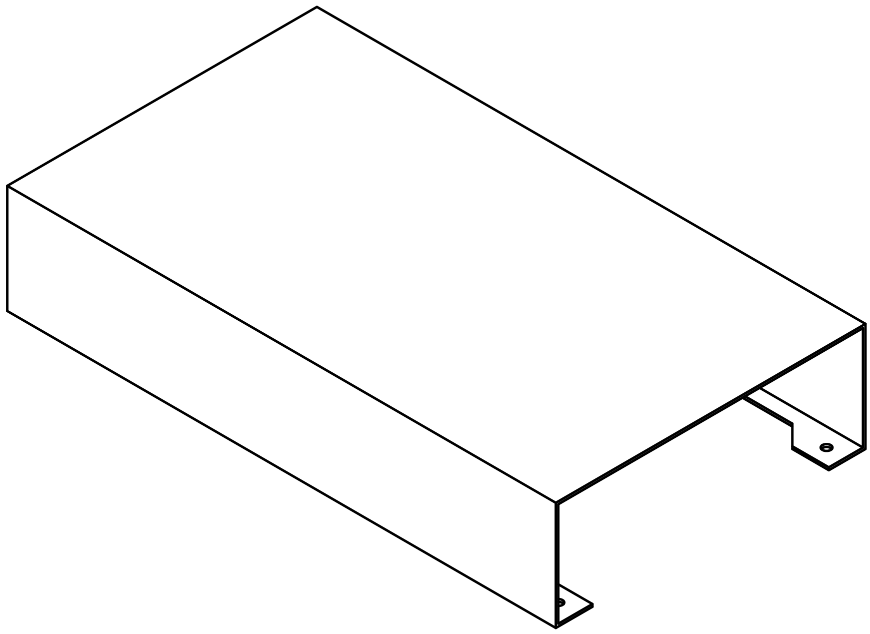
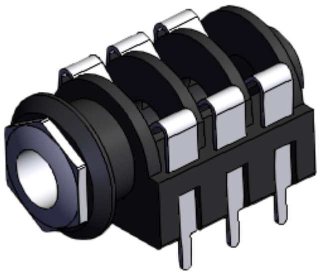


Figure 7.2: Scatch of the chassis enclosure.

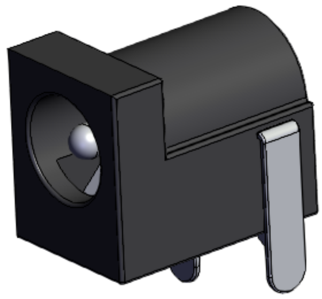
from underneath holding the amplifiers feet at the same time (see figure 7.2). The chassis also has a space on the top for additional electronics which is perfect for this tube design.

7.2 PCB separation and block design

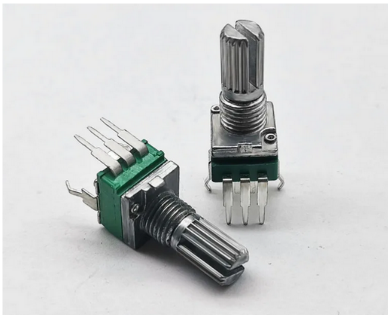
The PCB design aims to deliver reliability and overall market-standard quality of the device. Therefore it is highly limited by the selection of components (mainly connectors and potentiometers) so it fits well in the chassis. The device will be mainly designed for SMD assembly to lower the cost and space requirements except for the tube stage which due to the high voltage is required to use high voltage film capacitors and THT Schmidt trigger comparators so it is not very convenient to design it fully SMD. [3]
For the connectors, I chose Neutrik NMJ6HCD2 for the 6.3mm phono jacks, and the standard 3pin 2.1mm DC jack socket for the power input. For potentiometers, I chose RK097N vertical potentiometer. For the switches, I chose DPDT Sub Mini Toggle Switch - ON/ON - PCB Mount for the tube bypass switch and MTS-102-F1 for the power switch.



(a) : Neutrik NMJ6HCD2 phono jack connector.[28]

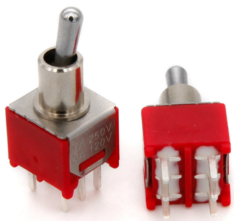


(b) : 2.1mm DC jack connector.[29]



(c) : Vertical potentiometer RK097N.[30]

(d) : Power switch MTS-102-F1.[31]



(e) : DPDT Sub Mini Toggle Switch for bypass.[32]

(f) : Tube socket Noval Belton, Print VT9.[33]

Figure 7.3: Selected connectors, switches, sockets, and potentiometers for the design.

This selection creates some limitations for the design to maintain the required reliability avoiding cable connections. For this reason, I decided to separate the PCBs into several units (see in block diagram in figure 7.4). The amplifier will be divided into six separate PCBs. The first four PCBs can be labeled as a functioning block of the preamplifier and the other two as the Power amplifier group.

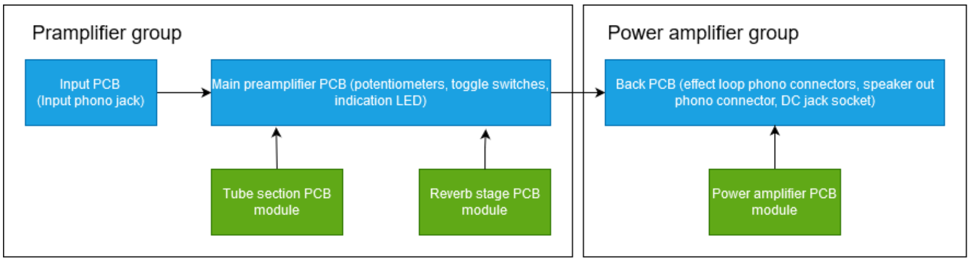


Figure 7.4: PCB design block diagram.

The resulting PCBs separated into individual units in the chassis can be seen in figure 7.5.

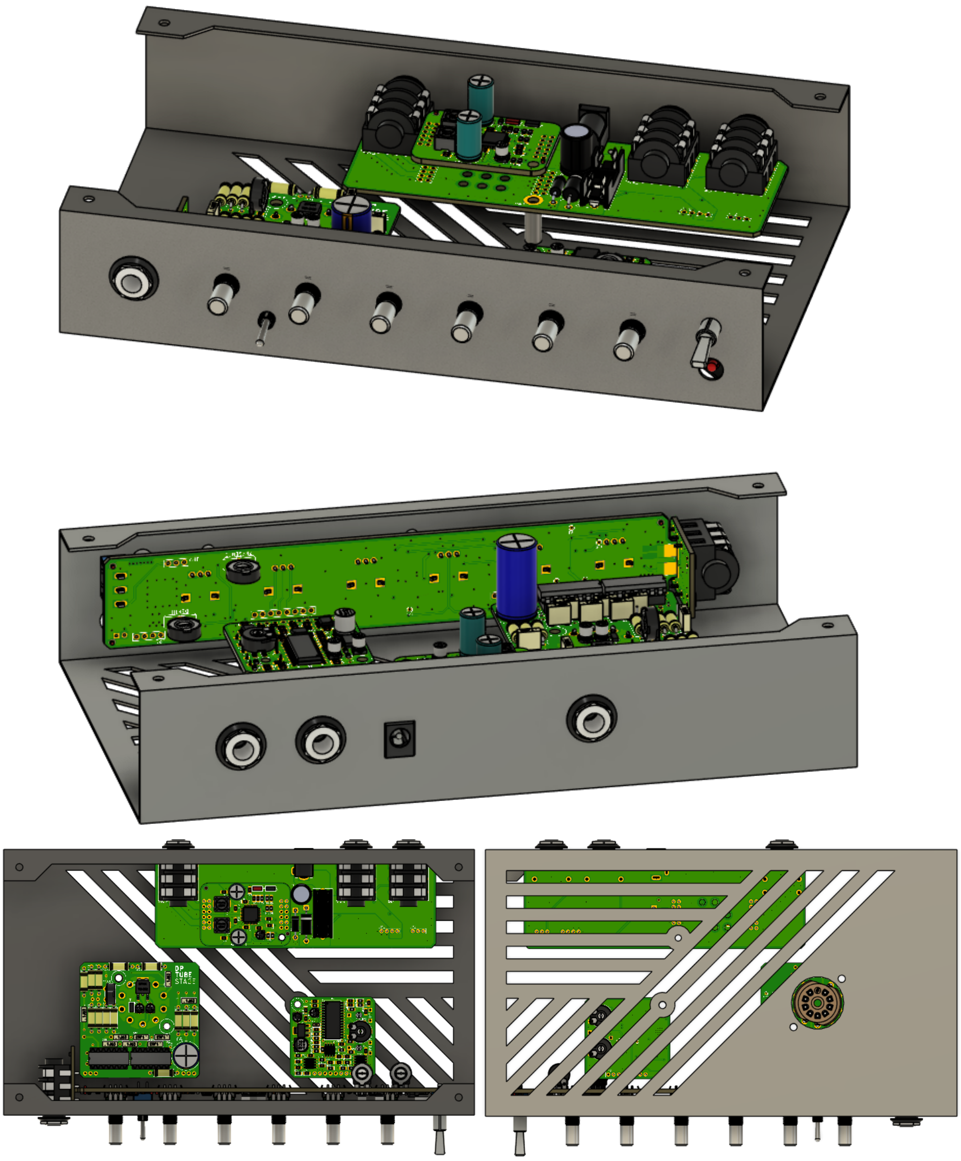


Figure 7.5: Amplifier PCB and chassis design.

7.3 Preapmlifier group of PCBs

This group of PCBs contains everything required for the complete functioning of the preamplifier and for the user front interface. All of these PCBs will be located at the front of the enclosure and will be fixed to the front panel with the potentiometers, switches, and phono jacks. The modules are separated and will be fixed to the top of the chassis with plastic M3 columns and screws.

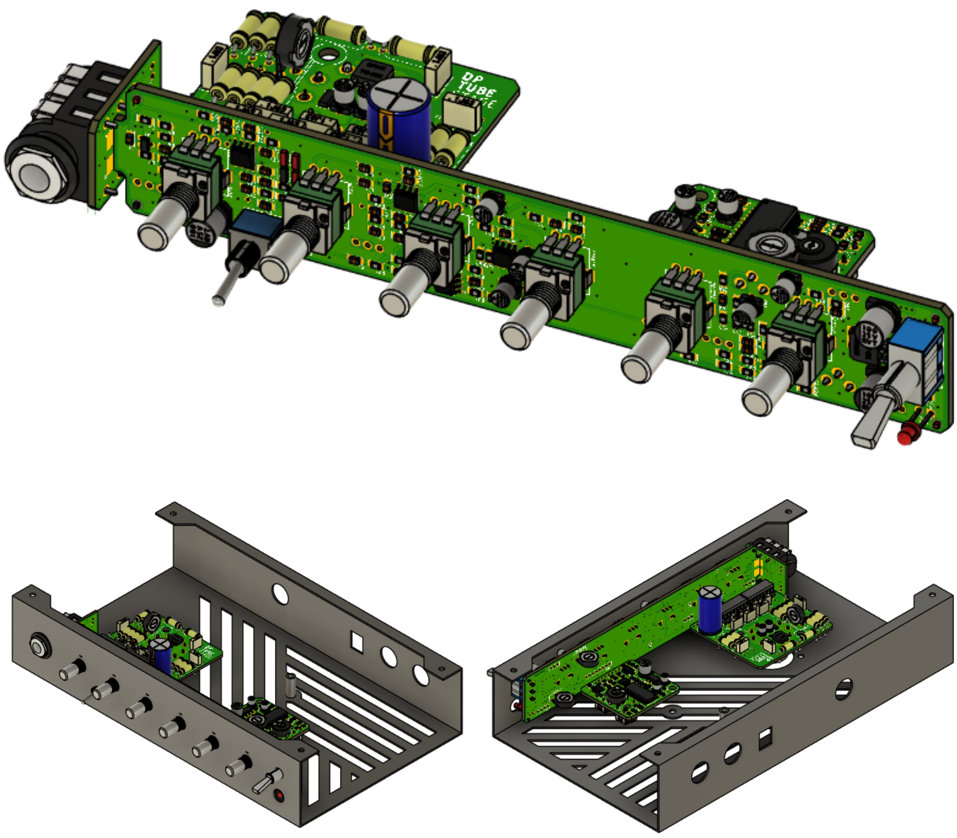


Figure 7.6: Preamplifier group of PCBs.

7.3.1 Input PCB

The input PCB is a simple 2-layer PCB that mounts the phono jack for the signal input of the Amplifier. The schematic can be seen in figure 7.7 below. The amplifier is a mono amplifier which means that the ring pins remain unused and the input PCB only uses the tip pin for the signal, the sleeve for the ground, and the TB pin which is a pin that is shorted to the tip when cable unplugged which I used to mute the signal input when the amplifier stays unplugged to minimize the noise on the device when unused and still turned on.

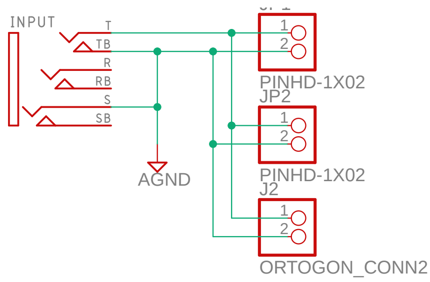


Figure 7.7: Scatch of the chassis enclosure.

The PCB offers three independent options for the signal to be connected to the main preamplifier PCB, two standard 2-pin cable slots, and one set of pads. This set of pads is designed to be paired with the preamplifier PCB and to sit at a right angle with the main PCB positioned close to a similar set of pads. This allows a strong and reliable connection when soldered and also allows the phono jack connector to be in line with the potentiometers. The PCB can be seen in figure 7.8.

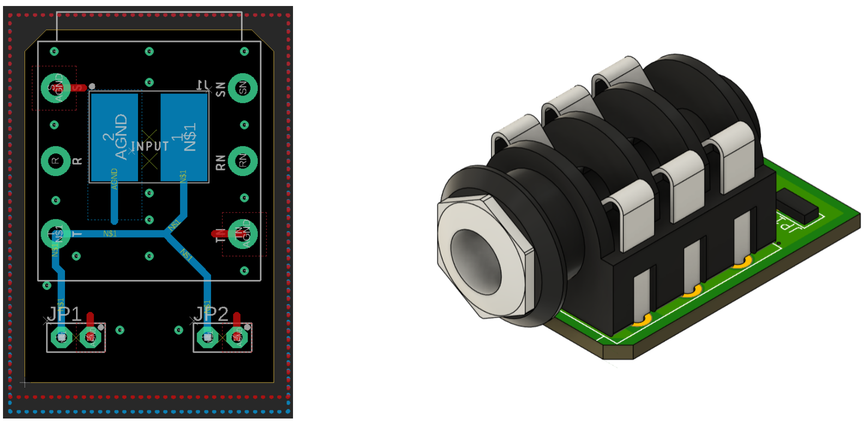


Figure 7.8: Input phono jack PCB.

7.3.2 Main preamplifier PCB

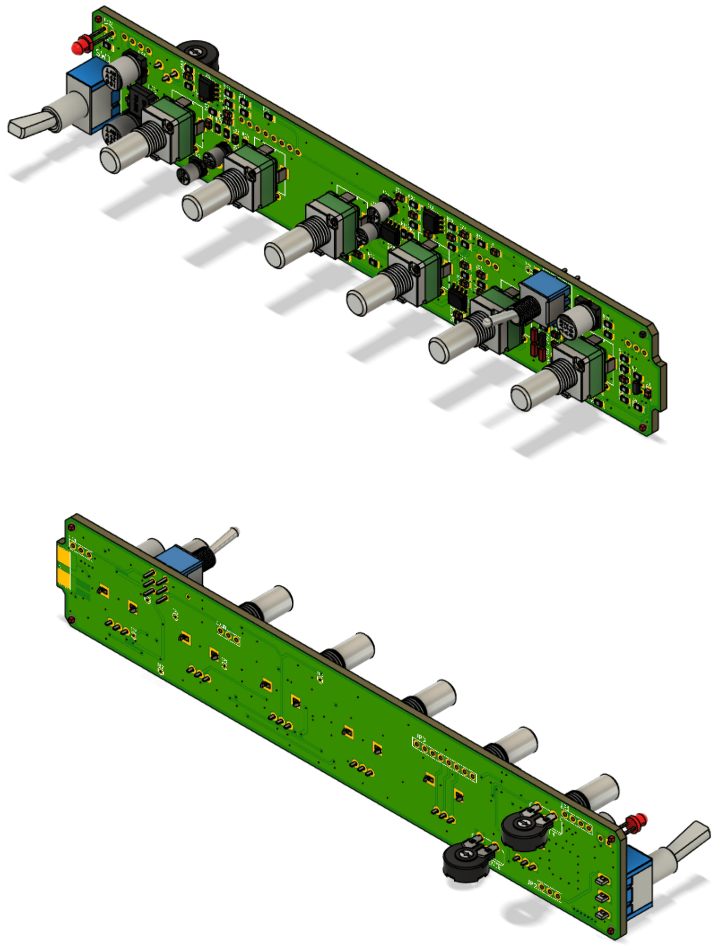
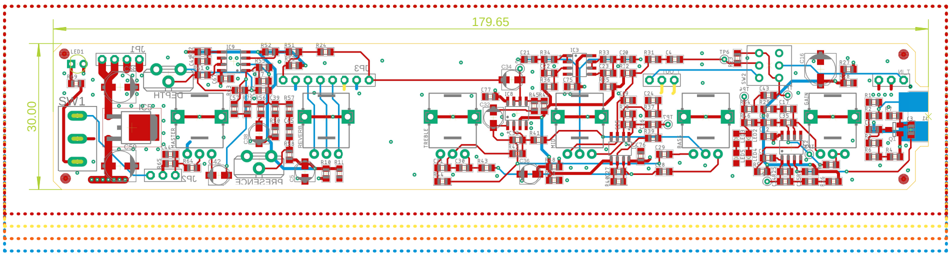
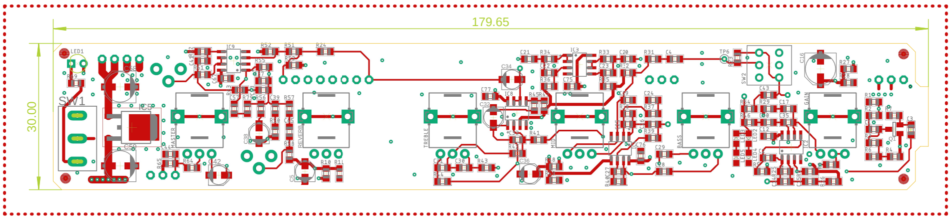


Figure 7.9: Preamplifier PCB model.

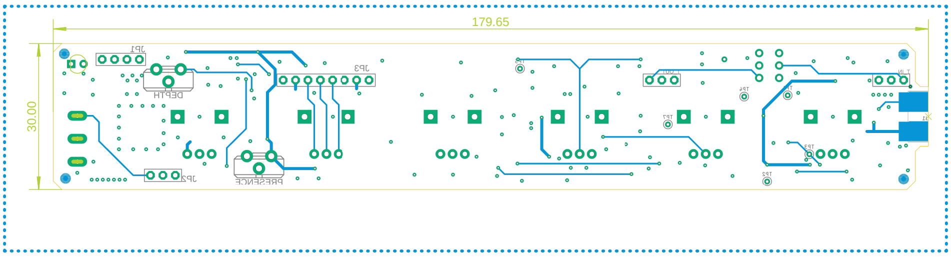
This PCB serves as the main PCB for the preamplifier and as the user interface. The PCB contains all controls including potentiometers, switches, and indication LED other than connectors. The schematic includes the input buffer and amplification stages (see figure 5.3), the true bypass switch of the tube stage (see figure 5.7), the three-band eq (see figure 5.10), the output stage (see on figure 5.14), the voltage regulator for the preamplifier and indication led including the main power switch (see figure 5.2).
The main preamplifier PCB is a four-layer PCB with internal layers used for the $VCC = 18V$ and ground to lower noise and power trace lengths. The top and bottom PCB have copper spilled grounded plates between components to also reduce the emitting and receiving noise to a minimum.



(a) : Preamplifier PCB all layers view.



(b) : Preamplifier PCB top layer view.



(c) : Preamplifier PCB bottom layer view.

Figure 7.10: Main preamplifier PCB.

7.3.3 Tube section PCB module

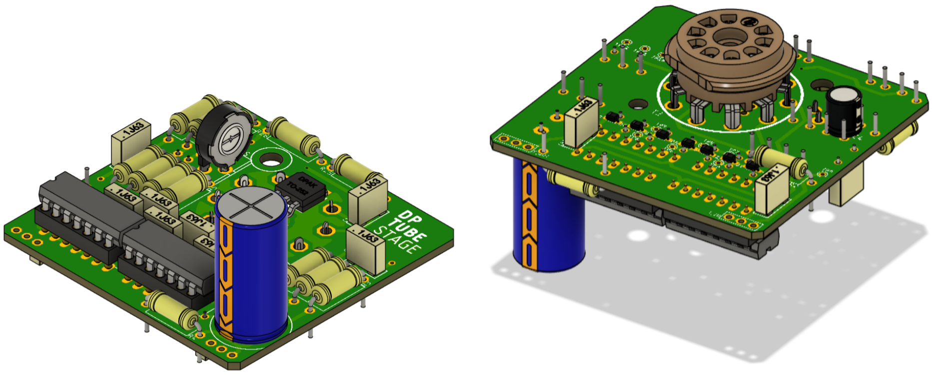
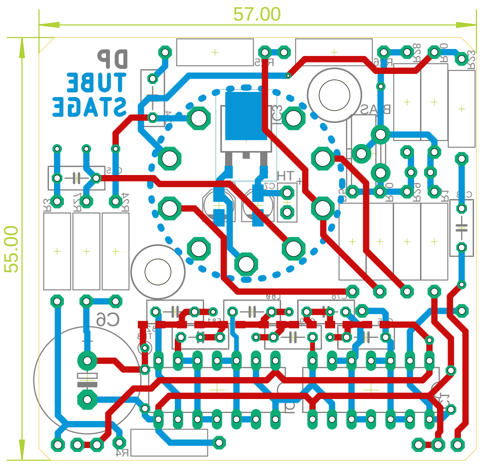
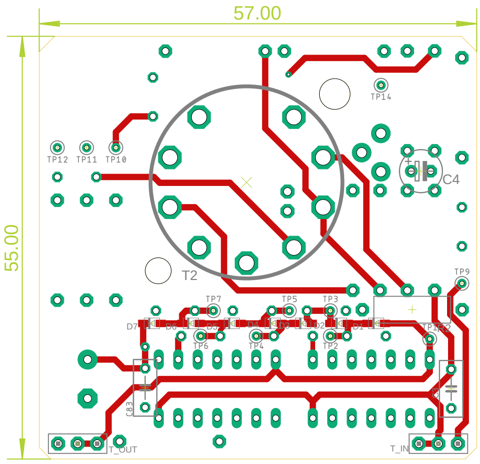


Figure 7.11: Tube section PCB model.

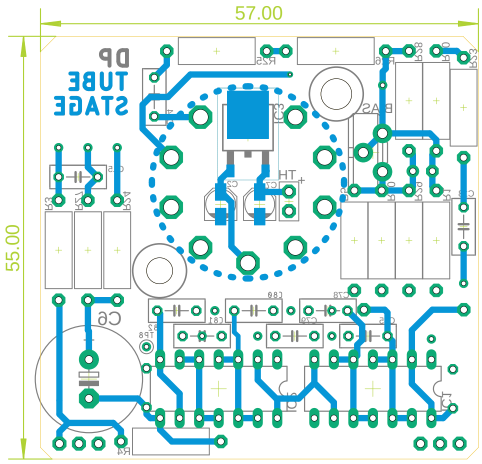
The tube section PCB module is a separate PCB module that is designed to stand parallel to the top side of the chassis and at a right angle of the main preamplifier PCB connected to it via two 3-pin right angle pin rows. The first pin row has one pin for the signal in and two for the ground, the second pin row has the signal out pin and two VCC pins.
The tube stage was designed mainly from THT components because of the high voltage which requires the use of film capacitors and 1/2W resistors which are both difficult and expensive to make and assemble as SMD components so I decided to design the PCB as THT components mainly with an exclusion of the SMD 1N4148 diodes since they are easy to solder by hand and it significantly simplifies the PCB design. Another SMD components I decided to use were the 12V regulator and its electrolytic capacitors for the heater since this way they fit nicely under the vacuum tube and the spilled copper ground is sufficient as a heatsink for the regulator. Also due to the higher voltage for the vacuum tubes, I decided not to use spilled grounded copper plates in the whole design (other than the heatsink of the regulator) since to fulfill the necessary spacing requirements the did not make much sense. I decided to fix the boards to the chassis with two screws close to the tube to limit the mechanical stress of the board when changing tubes.



(a) : Tube stage PCB all layers view.



(b) : Tube stage PCB top layer view.



(c) : Tube stage PCB bottom layer view.

Figure 7.12: Tube section PCB.

7.3.4 Reverb section PCB module

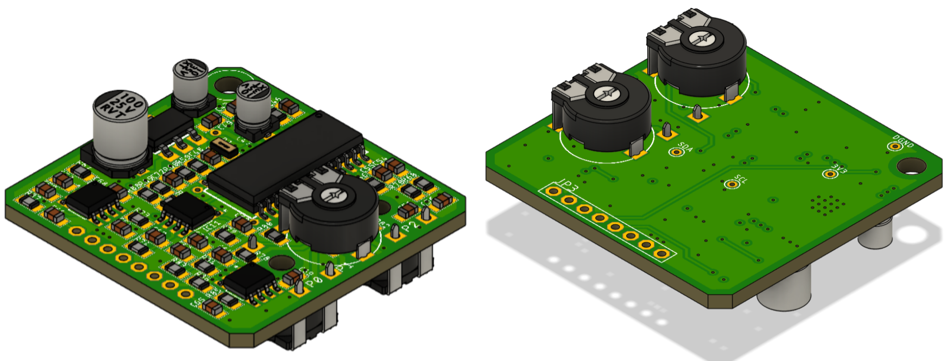
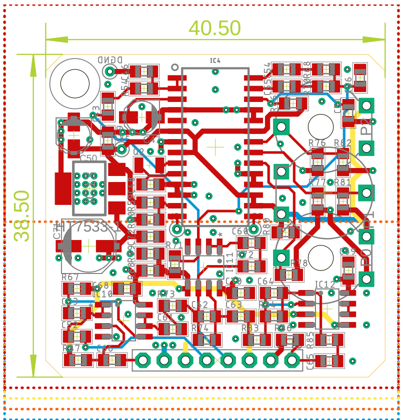
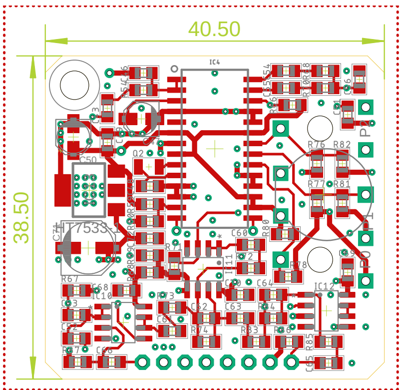


Figure 7.13: Reverb section PCB model.

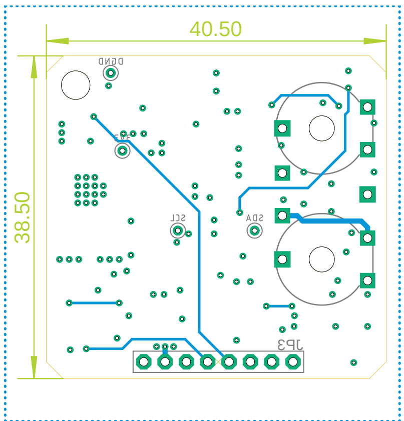
The reverb section is located and connected to the main preamplifier PCB in a similar way as the tube stage PCB. With a single 8pin right angle pin row it connects to the main PCB and the pins contain from right to left an input pin, two ground pins, one VCC pin, and three pins to connect to the Reverb potentiometer on the main preamplifier PCB, and an output pin. The three trimmers are placed in a way so that the user can change the setting with a screwdriver through a placed hole in the PCB (for the two trimmers hidden on the other side of the PCB) to keep the inside setting adjustable without taking the PCBs from the chassis.



(a) : The reverb section PCB all layers view.



(b) : The reverb section PCB top layer view.



(c) : The reverb section PCB bottom layer view.

Figure 7.14: Tube section PCB.

The Reverb section PCB is a four-layer PCB with the internal layers used for VCC and analog ground to reduce noise. The design separates analog and digital ground at the point of the 3V3 regulator. To lower the power trace lengths I set the top half of the PCB inner ground layer as digital ground. The PCB is fixed to the enclosure via one M3 column with a screw.

7.4 Power amplifier group of PCBs

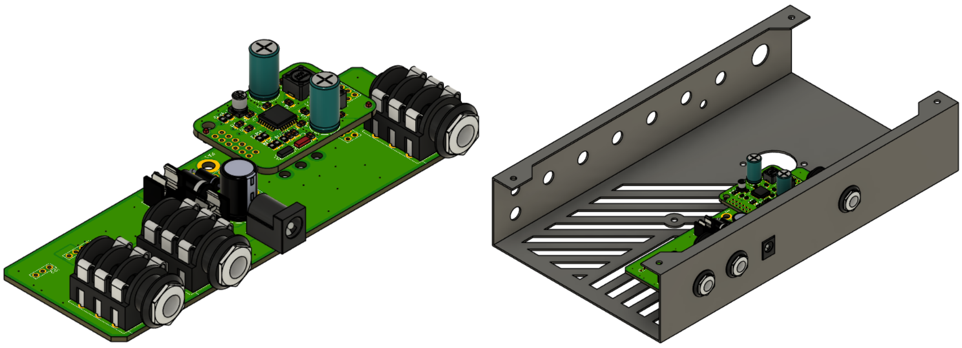


Figure 7.15: Power amplifier group of PCBs.

The power amplifier group of PCBs is supposed to take care of the power amplification, the effects loop, power protection, power distribution to the preamplifier, and the tube stage section and make a strong shielding connection with the chassis.

7.4.1 Back connector PCB

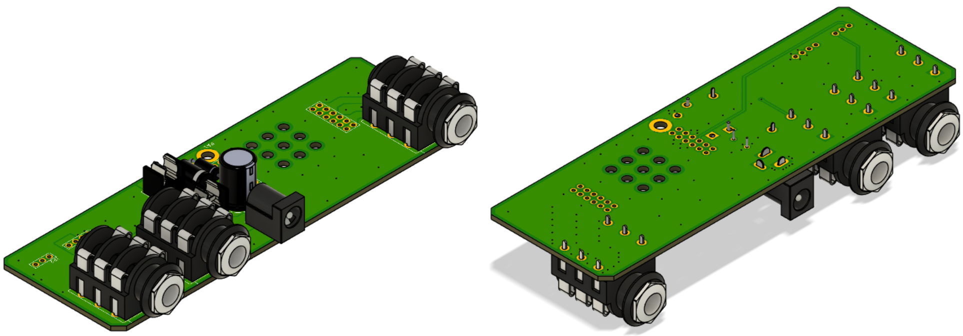
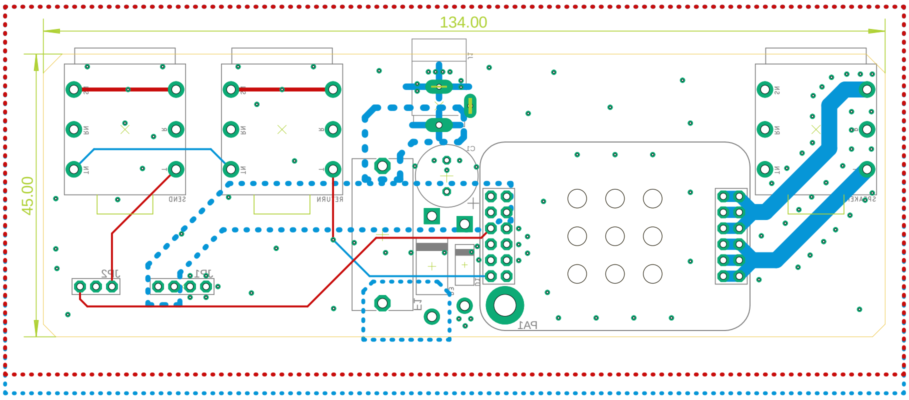


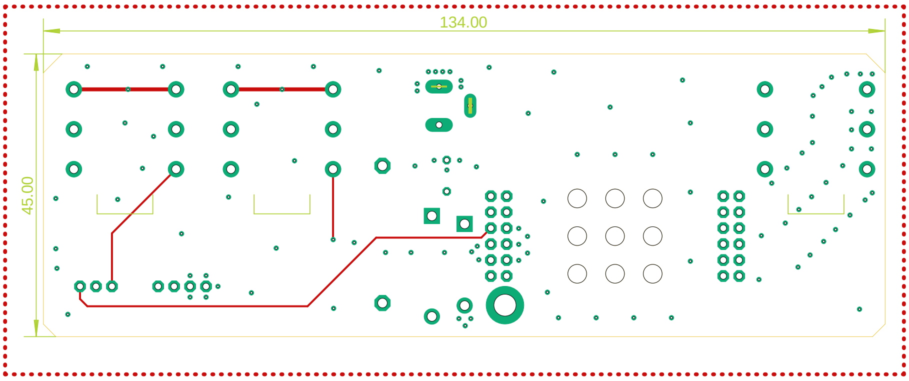
Figure 7.16: Back connector PCB model.

The back PCB is a two-layer PCB and is fixed to the back side of the chassis and contains the connectors for the effects loop, a 2.1mm DC jack power socket, and the speaker connector. The board takes care of the power protection and two pin rows, one for the power cable connection to connect to the preamplifier and the tube heating (two pin contacts each), a second to connect the shutdown signal, preamplifier out signal, and ground for shielding as it is aimed to connect to these signals with the preamplifier with coax cable. The PCB also connects with the power amplifier with two 2x6pin rows.

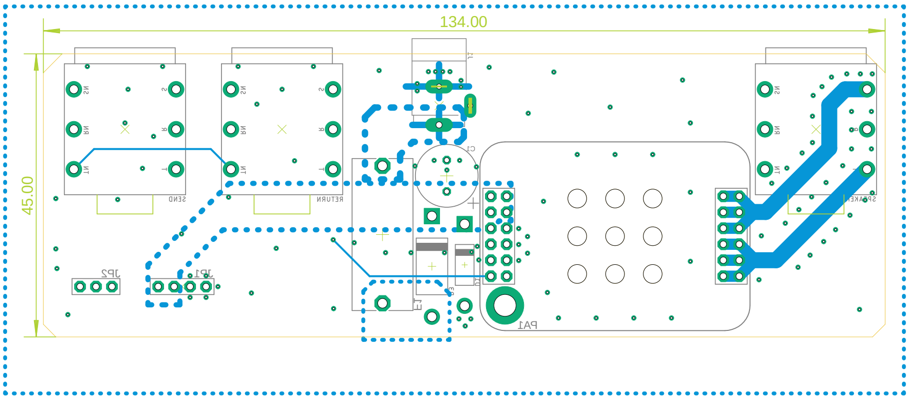
One pinrow is for the speaker output (6 pins for the speaker positive and 6 pins speaker negative), the second consists of 5 pins for the ground, 4 pins for the 24V DC power input, two for the signal input (positive and negative input) and shutdown pin. There is a copper-plated hole to fix the back PCB to the chassis and secure a strong chassis grounding. This copper-plated hole also aligns with the power amplifier for it to be fixed with a screw so the user cannot easily remove it.



(a) : The connector PCB all layers view.



(b) : The connector PCB top layer view.



(c) : The connector PCB bottom layer view.

Figure 7.17: The back connector PCB.

7.4.2 Power amplifier PCB module

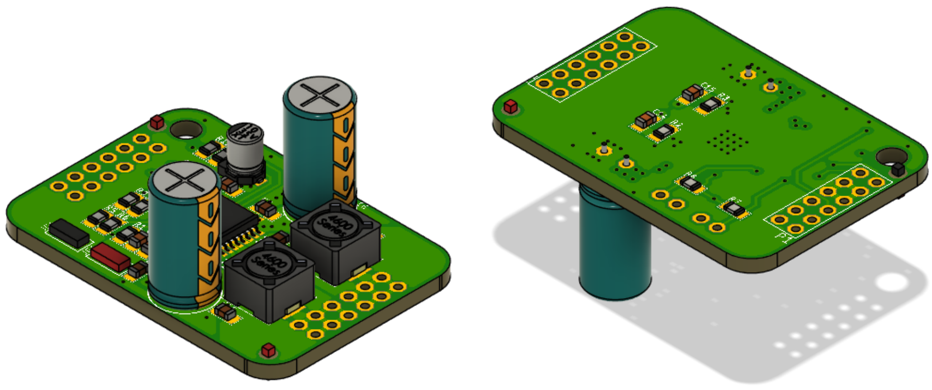
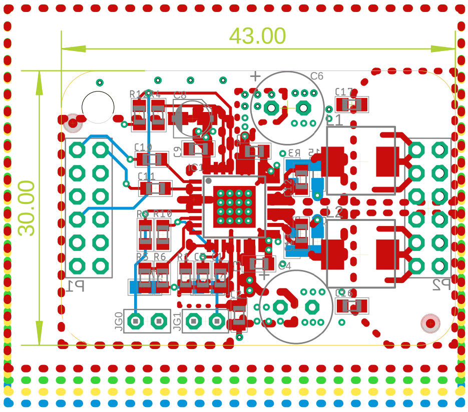
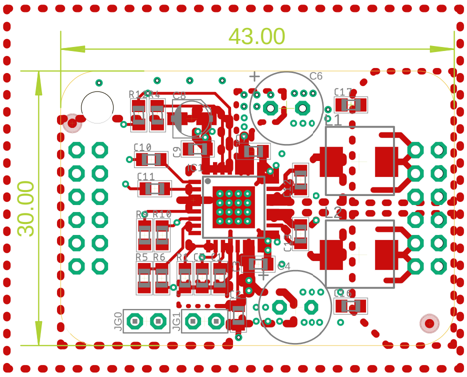


Figure 7.18: Power amplifier PCB model.

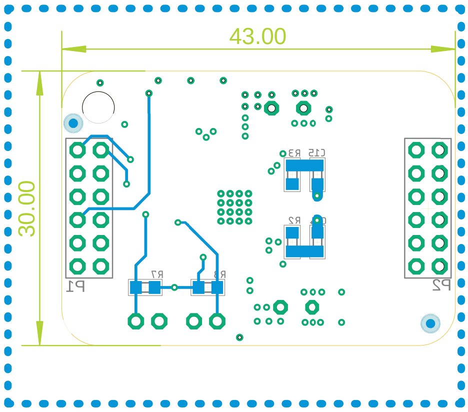
The power amplifier PCB contains the 40W class-D TPA3106D1 power amp. The design was strictly based on recommendations in the documentation and the evaluation board except the PCB being a four-layer PCB. The crucial component selection is low ESR electrolytic capacitors for the DC power source and shielded inductors on the speaker output. Another important design feature of the design is the heatsink. The amplifier produces 40W and even with its efficiency produces a lot of excess heat that is transferred from the power pad on the bottom of the TPA3106D1 to the heatsink created by grounded copper plates connected through all four layers with vias.[9]
There are several copper planes in this PCB design. The output signals from the chip are designed as copper plane polygons to lower the noise received on the low-impedance outputs. There are power and analog grounds separated as advised in the datasheet. The inside layers are used as copper planes, one as a power ground for the 24V power supply. The top and bottom layers are used for copper plane grounds.



(a) : The power amplifier PCB all layers view.



(b) : The power amplifier PCB top layer view.



(c) : The power amplifier PCB bottom layer view.

Figure 7.19: The power amplifier PCB.

7.5 Mechanical design

The PCBs are designed to sit in a metal chassis as seen in figure 7.2. To securely hold the PCBs in the chassis and also allow enough air and heat exchange in the chassis I edited the milling of the chassis and designed the enclosure as it can be seen in the figure 7.20 below (the complete 1:1 drawings can be seen in the attachments). I also designed a metal plate as the main cover of the front opening with the CTU logo which was laser cut at NC Wega (with the chassis also) and will be fixed at the front of the wooden shell (see figure 7.21).

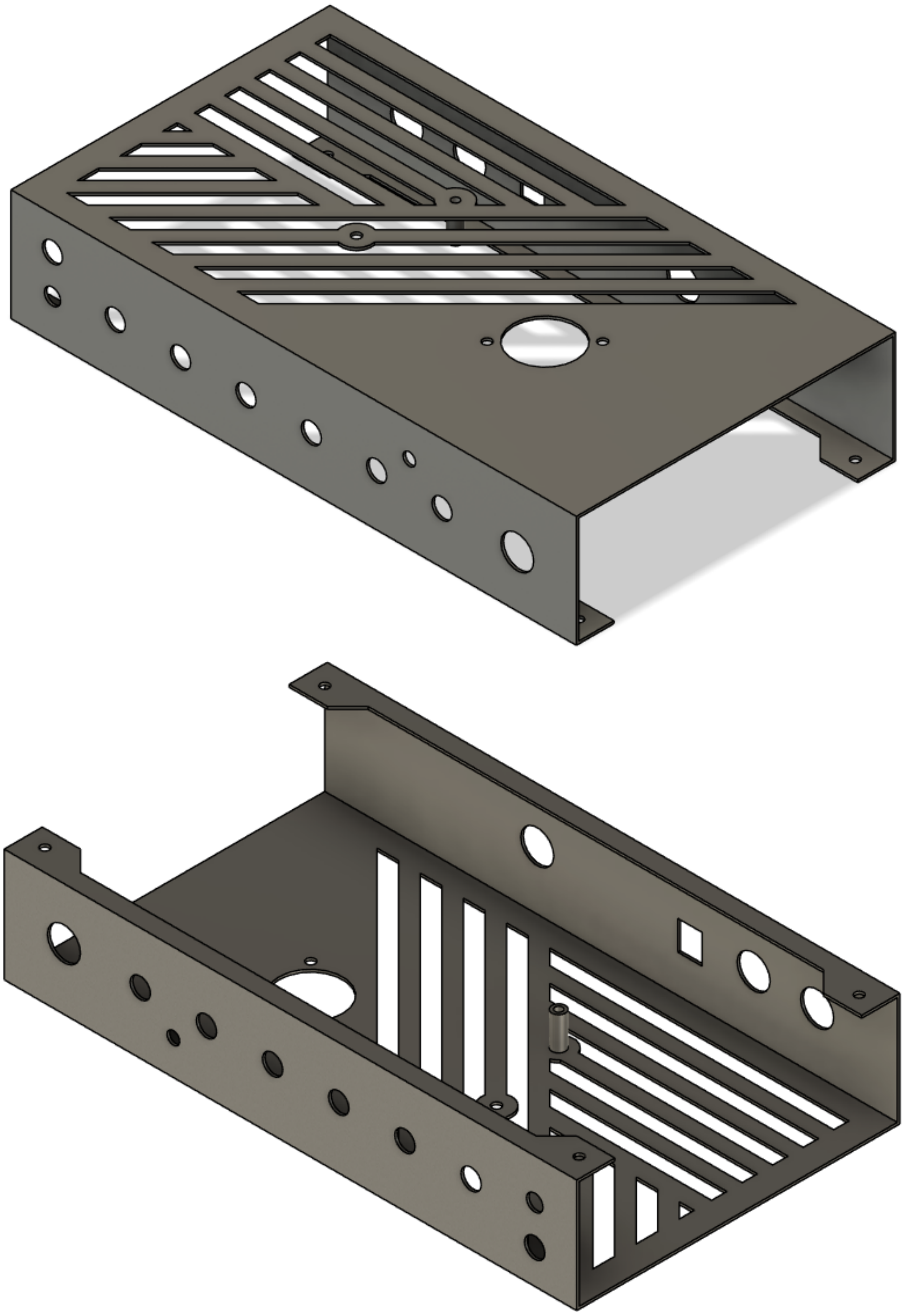


Figure 7.20: Designed metal chassis enclosure.

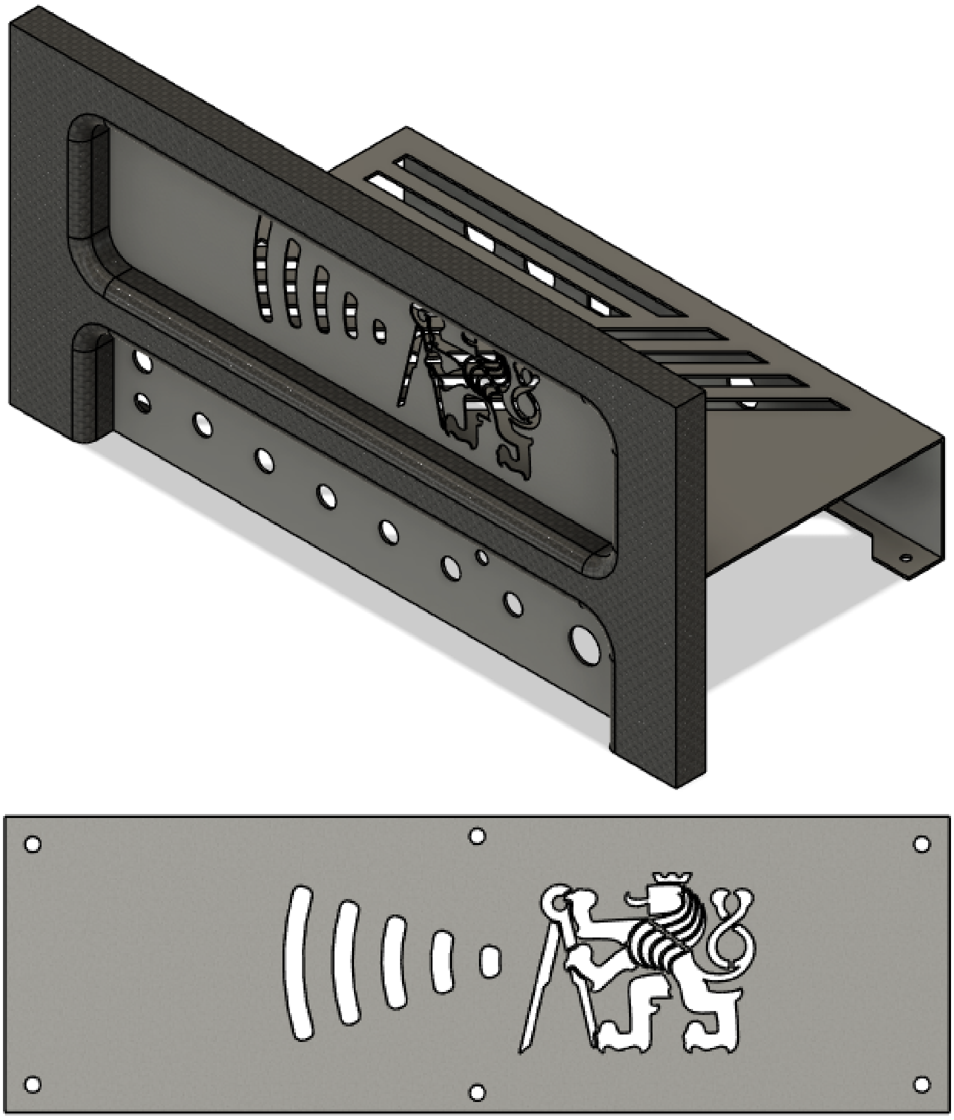


Figure 7.21: Designed metal chassis enclosure with the front CTU logo plate.

Part III

Prototype assembly, testing and measurements

Chapter 8

Prototype assembly and testing

8.1 Prototype assembly

The PCBs were assembled based on the schematics in the design chapter. You can see the assembled PCBs in the picture in figure 8.1. For testing purposes and to ensure enough backup devices I assembled three pieces.

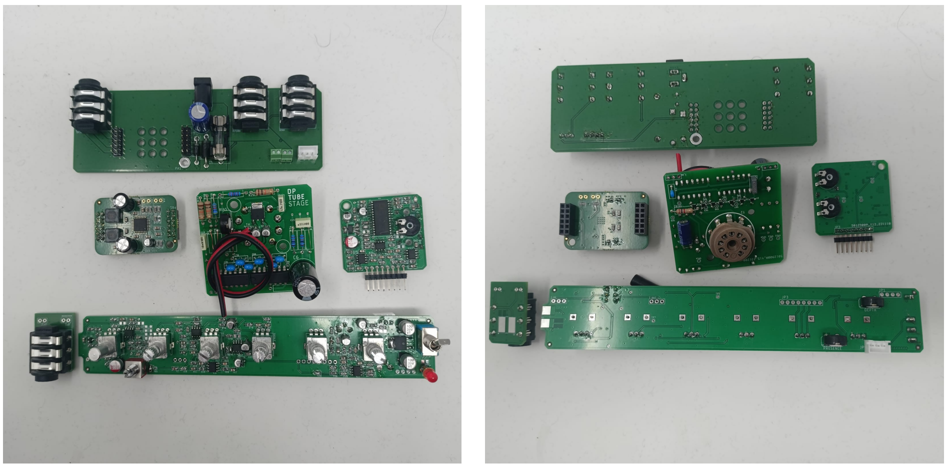


Figure 8.1: Assembled prototype PCBs.

The PCBs were fitted to the enclosure with all necessary cable connections and right-angled pin rows. The result can be seen in the picture in figure 8.2.

Figure 8.2: The assembled prototype in chassis.

.

Figure 8.3: The assembled prototype in chassis.

8.2 First start and testing

To start and test if the device functions properly I followed this procedure:

1. Back PCB testing
   - measured the output voltage that is supposed to power the power amplifier and preamplifier
   - tested the overvoltage protection and reverse voltage protection
   - the fuse burnout after the voltage output was shorted
2. Power amplifier PCB testing
   - plugged into the back PCB and measured the voltage on individual power source pins of the TPA3106D1 chip

- plugged in a signal source into the return of the effects loop and checked the output signal on the resistor voltage divider with an oscilloscope
- plugged in a guitar as a signal source and 8 loudspeaker to the speaker output and tested the functionality

3. Preamplifier PCB testing
   - connected the power cables to the power protection output of the back PCB and measured the output of the 18V linear voltage regulator
   - tested the Mute function of the main ON/OFF toggle switch by turning it off (muting the signal path) and checked the output of the power amplifier is off
   - soldered on the input PCB and plugged in a guitar as a signal source and check the signal output of the preamplifier via effects loop send phono jack connector while Tube bypass switch being in the bypass position and reverb section path being bypassed
   - set up the inside trimmers of Depth and Presence
   - check the proper function of the signal path from the amplifier input with guitar as a signal source plugged in while 8Ω loudspeaker plugged into the speaker output
   - first check of the potentiometer functionality - Master is affecting the overall volume from zero to full volume properly, Gain potentiometer amplifies the signal as desired, Bass, Middle, and Treble affects the frequency spectrum as planned (so far just by ear)
4. Reverb PCB section testing
   - soldered in the reverb PCB section via right-angled pin row and measured the reverb section internal 3.3V regulator voltage output
   - plugged in a guitar as a signal source, set up the reverb potentiometer to a minimum, and checked the output ensuring only a dry signal on the output
   - set the reverb potentiometer first on half of the range, then on full and checked that the reverb effect is getting produced and that the potentiometer affects the reverb signal path volume as desired
5. Tube section PCB testing
   - soldered in the PCB section via right-angled pin row and measured the voltage multiplier output before connecting the anode resistors, then connecting them and measuring the voltages on the tube's pins
   - connecting the cables for the tube heater and measuring the voltage output on the 12V linear voltage regulator and visually checking if the tube emits light and starts heating up

- switching the tube bypass switch into on mode and running the guitar signal through while the loudspeaker is plugged in

6. Overall amplifier testing

    - main overall test of the individual features. Check all potentiometers if they (by the first personal impression) do what they were designed for. Check the effects loop if the preamplifier Dend works as the desired preamplifier signal output, Return as an input of the power amplifier, and works flawlessly when cables are unplugged.
    - longer run of the amplifier to check if any part is overheating, especially the voltage regulators and heated tube

When the testing of the individual features was done, I finished the prototype by putting it into the wooden shell. You can see the results in figure 8.4. After these individual tests and observations were finished, we continued with measurements.

Figure 8.4: The finished prototype of the amplifier front.

Figure 8.5: The finished prototype of the amplifier back.

Chapter 9

Measurements

9.1 Power consumption

Power consumption was measured to better understand and determine the power transfer inside the amplifier. The power distribution can be seen in figure 9.1. I chose six points of the power transfer to measure current drawn

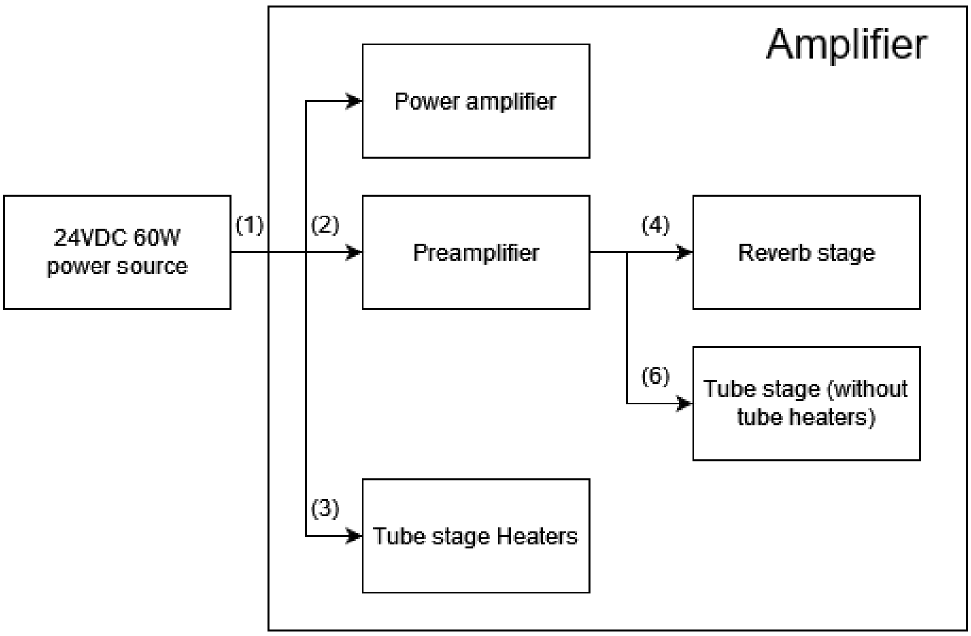


Figure 9.1: Amplifier power distribution measurements.

I_C at individual voltages U_C:

1. The complete power consumption of the whole device with every stage connected - measured current being drawn from the 60W power adapter at 24V
2. Power consumption of the standalone preamplifier PCB and the preamplifier PCB
3. Power consumption of tube heater
4. Power consumption of the Reverb stage
5. Power consumption of the Tube stage (without heaters)

Since the class-D, TPA3106D1 consumes power dynamically based on the output power I prepared the measurement with a guitar looper pedal on the input (to simulate a typical application with plain chord strumming) and a $10\Omega/20W$ resistor on the speaker output as an artificial load.[26, 19, 27] I set the reverb potentiometer to the minimum (so that it is only a dry signal going through), the gain potentiometer, and the equalizer to half of the range. The preamplifier setting's influence on the power consumption other than the overall output volume is negligible and therefore not considered or measured. I measured the power consumption over several preamplifier output volumes by setting the Master volume potentiometer. The current drawn I_C was measured with a multimeter UNI-T UT131A measuring the voltage drop over $1\Omega/20W$ on the DC input of the whole amplifier. This method is usable since we are only aiming to roughly compare the power amplifier and preamplifier power consumption. The power consumption was calculated as $P_C = U_C \cdot I_C$ and the results are in table 9.1 below:

Point of measurement	Volume [%]	U_C [V]	I_C [A]	P_C [W]
(1) Complete power consumption	0	24.5	0.311	7.6
(1) Complete power consumption	25	24.5	1.203	29.5
(1) Complete power consumption	50	24.5	1.998	48.9
(1) Complete power consumption	75	24.5	2.170	53.1
(1) Complete power consumption	100	24.5	2.210	54.1
(1) Complete power consumption in off mode	0	24.5	0.279	6.8

Table 9.1: Power consumption measurements results for the whole amplifier with power amplifier and artificial load.

Since the influence on the power consumption when there is a signal coming through is negligible, the next measurements were measured without the artificial load, with no signal going through, and without the power amplifier. The results can be seen in the table 9.2 below. The power consumption was calculated as $P_C = U_C \cdot I_C$. From the results, we can see that the overall

Point of measurement	U_C [V]	I_C [mA]	P_C [W]
(2) Preamplifier PCB group	23.6	278	6.8
(2) Preamplifier PCB (without Tube and reverb section)	23.6	21.8	0.5
(3) Tube heater	23.6	166	3.9
(4) Reverb stage	18.3	65	1.2
(5) Tube stage (without heater)	18.3	12	0.2

Table 9.2: Power consumption measurement results for the preamplifier's group of PCBs.

preamplifier's power consumption is $P_C = 6.8W$ and the heaters take $3.9W$ out of that. Compared to the power consumption of the whole amplifier with volume on maximum $P_C = 54.1W$ we can say that the power consumption of the preamplifier is negligible other than the tube heater as assumed.

9.2 Equalizer trasfer functions

To ensure the three-band equalizer works as requested I measured the frequency characteristics of different settings. The equalizer was measured from EQ_IN (before coupling capacitor C18) to R_IN (reverb in, past coupling capacitor C34), see in figure 9.2

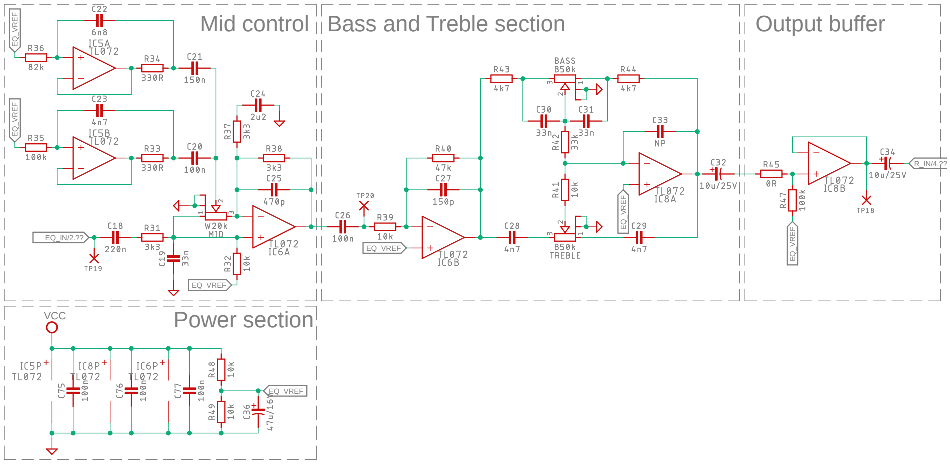


Figure 9.2: Schematic of the designed three-band equalizer.

The measurement was done with Velleman PCSGU250, a two-channel PC oscilloscope with a generator that offers in its software also a circuit analyzer. This option generates sinus functions of different frequencies and measures the response of the system to the output. I selected the 10% frequency step and the results were plotted with Matlab. I measured the lowest, middle and highest range position for bass (see figure 9.3), middle (see figure 9.4), treble (see figure 9.5) individually (with the rest potentiometers set to the middle) and all potentiometers at the same time (see on figure 9.6).

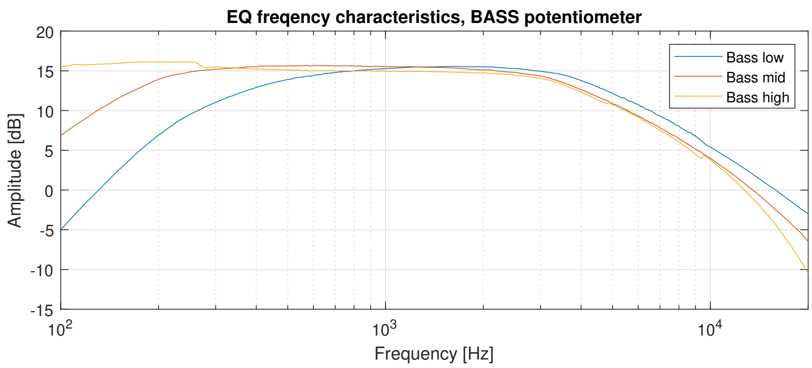


Figure 9.3: Frequency characteristics of the EQ, bass changing.

We can see that the bass control works as required.

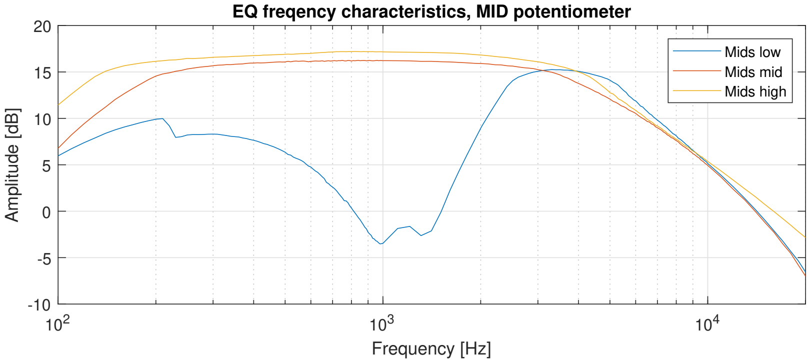


Figure 9.4: Frequency characteristics of the EQ, middle changing.

The middle potentiometer does not work as planned, we can see that the cut option cuts the signal around $1kHz$ properly but does not boost the selected frequencies as assumed. It boosts the whole frequency range by approximately $1dB$ which is also usable but not enough as desired.

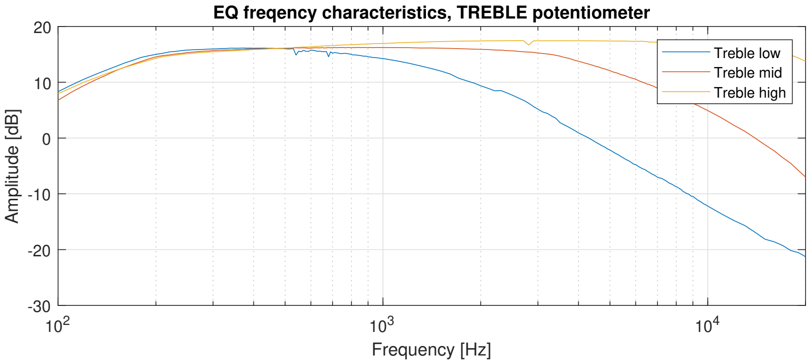


Figure 9.5: Frequency characteristics of the EQ, treble changing.

The Treble control works as required, we can see a boost and cut over $1kHz$.

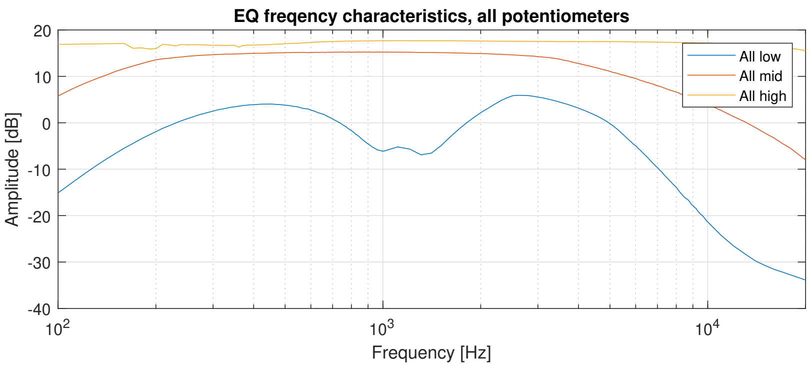


Figure 9.6: Frequency characteristics of the EQ, all potentiometer changing.

The equalizer works slightly differently than expected. It was expected to boost the frequencies at maximum, remain unchanged in the middle position, and cut in the minimum setting. The maximum setting boosts all frequencies as required, and the minimum setting cuts the bass, middle, and treble but the middle position still cuts the bass and treble frequencies. But the potentiometer allows all positions between minimum and maximum settings, it is still usable in this application since we don't require precision positioning of the potentiometer and it can be set individually by the user.

9.3 THD of the power amplifier

The TPA3106D1 chip used for the power amplifier is specified to have a 0.2% THD+N for a $1kHz$ frequency signal. To measure and verify this statement I prepared an experiment.[8]
The total harmonic distortion (THD) is defined as a ratio of RMS amplitude values of higher harmonics $V_i, i > 1$ to the RMS amplitude of the fundamental frequency V_1:

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} V_i^2}}{V_1} \cdot 100 \doteq \frac{\sqrt{\sum_{i=2}^{i_{max}} V_i^2}}{V_1} \cdot 100 \tag{9.3.0.1}$$

The higher harmonics RMS amplitude values are descending so for calculating purposes we only consider a limited number of harmonics $i_{max} = 20$.[34, 35]
The measurement consists of a function generator 24-bit DAC converter playing a prepared audio file consisting of the fixed frequency sinusoidal signal, a sound card Zoom F6 MultiTrack Field Recorder to record the signal, and the actual power amplifier with a 10W power resistors as an artificial load (with 10:1 ratio of 10Ω and 1Ω). The block diagram of the experiment can be seen in figure 9.7.[13]

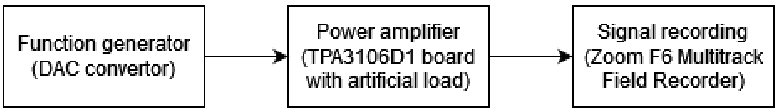


Figure 9.7: Block diagram of the THD measurement experiment.

To calculate the THD from the recorded signal I used fast Fourier transformation (fft in Matlab) and isolated the frequency spectrum only for half of the sampling frequency $Fs/2 = 44100/2Hz = 22050Hz$. Since the spectrum of the discrete signal stretches the energy of the individual harmonics I calculated the RMS amplitude values for the i-th harmonic as:

$$V_i^2 = \sum_{j=i-w}^{i+w} v_j^2 \tag{9.3.0.2}$$

where v_j are the absolute amplitude values of the spectrum for frequency j. The w is half of the chosen width of the frequency spread which I chose as $w = 10$. This number says how many points $total\ points = 2 \cdot w$ of the spectrum are considered in the calculation.[34]
The processed spectrum can be seen in figure 9.8. The fundamental frequency points are colored yellow, the higher harmonics purple and the leftover spectrum points (noise) blue. For better visualization there is a zoomed (in amplitude) spectrum in figure 9.9.

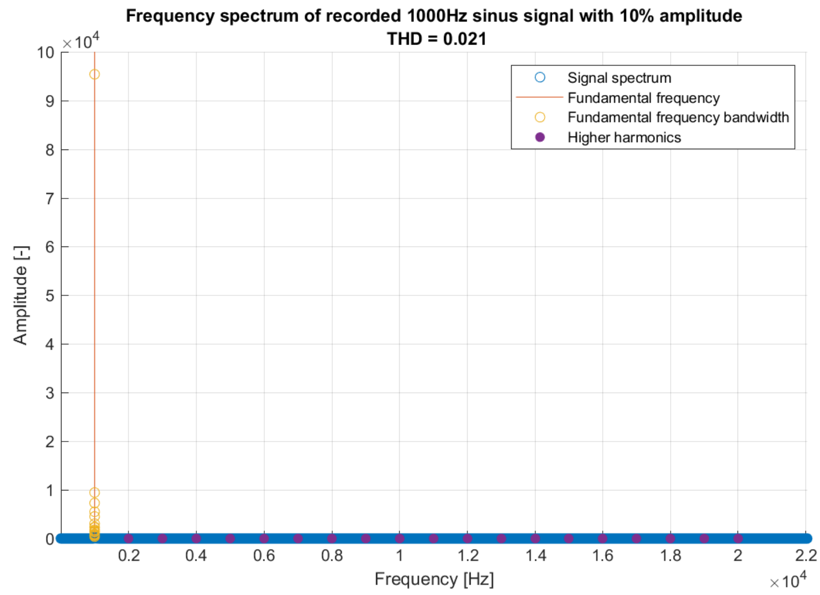


Figure 9.8: Frequency spectrum of the 1kHz signal.

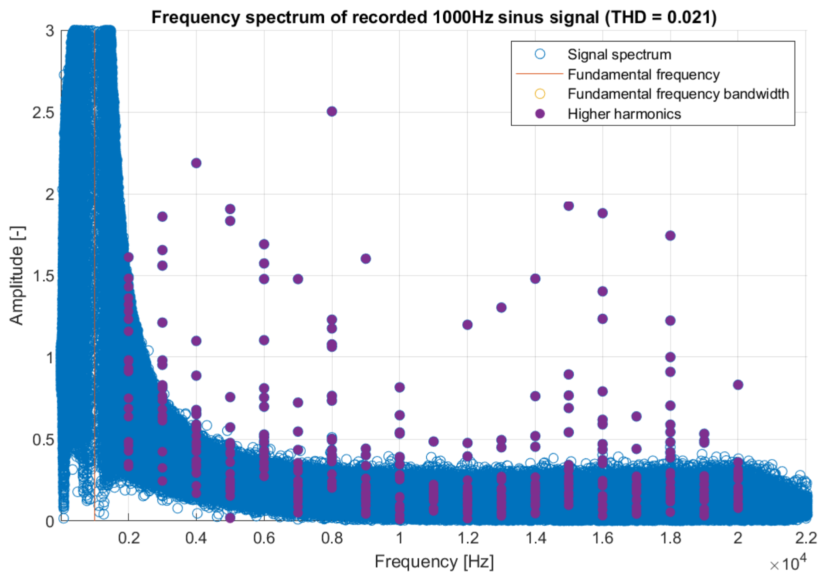


Figure 9.9: Frequency spectrum of the 1kHz signal.

I processed signals and calculated THDs for 100, 200, 500, 1000, 2000 and 5000Hz frequencies. The results are in the table 9.3 below and on a graph in figure 9.10.

Frequency [Hz]	100	200	500	1000	2000	5000
THD [%]	0.056	0.034	0.015	0.021	0.036	0.076

Table 9.3: THD results for individual frequencies.

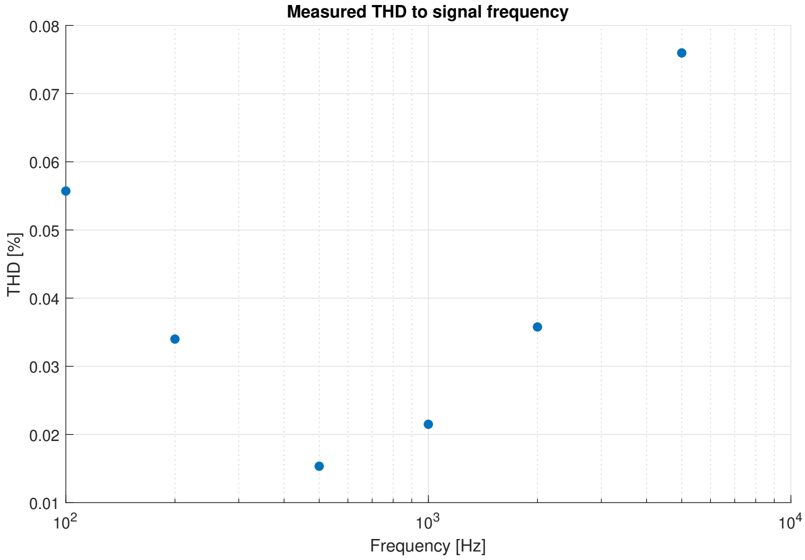


Figure 9.10: THD results for individual frequencies.

The THD of the power amplifier when amplifying 1kHz signal was measured as $THD_{measured,1kHz} = 0.21\%$ which corresponds to the datasheet value $THD + N = 0.2\%$.[8]

Part IV

Results, conclusion, and future improvements

Chapter 10

Conclusion

10.1 Results

I designed a fully working guitar amplifier with user controls according to the setup requirements. All controls work as required. The amplifier is powered by a $24VDC/60W$ power supply and consumes when on maximum amplification power around $55W$. Most of it is drained by the power amplifier and the tube heater. In off (power saving mode) it drains around $6.8W$ where $4W$ takes the heater and rests the preamplifier which runs all the time.
The main gain stage of two non-inverting operational amplifiers with an input buffer works as required.
The voltage multiplier of the tube section outputs around $120V$ for the cathodes with approximately $12mA$ current being drawn and outputs enough current to feed the tube without noticeable noise on the output. The tube's heater drains approximately $4W$. The PCBs are designed in a way that for low power consumption, the tube stage can be cut out and the device works on quite low power consumption.
The three-band equalizer works as desired and I measured its setting's frequency characteristics for minimal/maximum setting. The Bass control at $164.81Hz$ (fundamental harmonic of the low E guitar string) delivers a gain setting from $3.5dB$ to $16dB$ gain. The middle does not noticeably gain the middle frequencies but rather amplifies the whole frequency spectrum (see figure 9.4) but cuts the mids at $1kHz$ to $1.3kHz$ for around $5.5dB$ on minimum. The treble cuts and boosts the $5kHz$ frequency from $-2dB$ to $17dB$. See the actual measured frequency characteristics at figures 9.3, 9.4, 9.5 and 9.6.

The reverb stage works around the audioprocessor FV-1 and uses an integrated Reverb program. It allows the user to change the reverb length, reverb treble damping, and reverb echo bass filtering via a set of inside trimmers and a front face control of the reverb echo amplitude.
The output stage offers outside control of the Master volume and also allows the final frequency corrections of Depth and Presence.
The power amplifier is a class-D amplifier TPA3106D1, which offers 40W amplification with an overall power consumption of around $50W$ when on maximum. It drains power dynamically depending on the output volume and drains $<< 1W$ when in off (Mute mode) without any heatsink other than integrated PCB. The measurement confirmed the THD value at $1kHz$ as 0.2% as being said in the datasheet.

10.2 Future improvements

For future developments for example next generation prototype I would add an option of turning off the heaters when in power-safe mode. The heaters still take quite a considerable amount of energy and in the case of an amplifier that is supposed to run for a long time without turning off (opposite to in comparison a guitar pedal), it would be preferred to consume less power in an off mode rather than the tube being heated and ready when turned on.
The preamplifier PCB group drains below $300mA$ current including the tube heater. This means that the heater could be powered directly from the preamplifier's $18V/500mA$ without any considerable damage or problems but since the heater takes almost $200mA$ out of that, ground loop noise should be tested and taken care of.
Another feature to improve should be the middle control of the three-band equalizer so that it offers a narrower bandwidth getting boosted.
A nice feature to add would be an option of integrated accumulator cells such as 12V lead batteries running in series to produce 24V. A typical AVACOM battery 12V 9Ah F2 HighRate [36] could run at a typical 50% volume (draining approximately $2A$ at $24V$) for at least four hours.
Since the class-D amplifier works well and the voltage multiplier as well, it creates a question of designing an all-tube preamplifier with a voltage multiplier as a voltage source for the cathodes. Since the parallel stacking works well with the PCB layout it creates an easy-to-integrate building block producing with two used parallel Schmidt trigger units (CD40106BE chips) around $I_{out} = 2 \cdot 6.8mA = 13.6mA$ output current and the dual triode tube (typical for guitar tube preamplifiers) drains at most with $100k\Omega$ cathode resistors at $U_C = 120V$ around $I_C = 2 \cdot 120/10^5 A = 2.4mA$ we can assume that it could power up to five dual triode tubes which are sufficient with most typical tube preamp designs (where most does not get higher than three

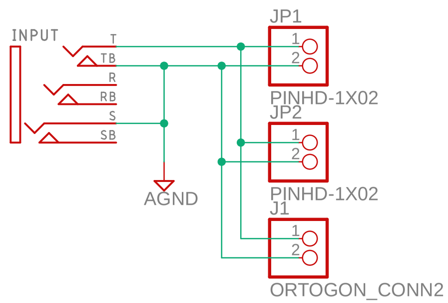
dual-triode tubes). For more than two dual triode tubes the power supply would be insufficient but either raising it or lowering the output power would work. An amplifier combining the class-D power amplifier and an all-tube preamplifier with this voltage pump would be a good choice for the next project.

10.3 Overall conclusion

The amplifier meets the requirements and expectations. It delivers a good-sounding amplification with plenty of power for practicing even when playing with a band. The outside user controls deliver a wide range of settings and combined with the internal settings even more. The enclosure gives good mechanical protection and housing.

Figure 10.1: Photos of the finished amplifier.

Appendices



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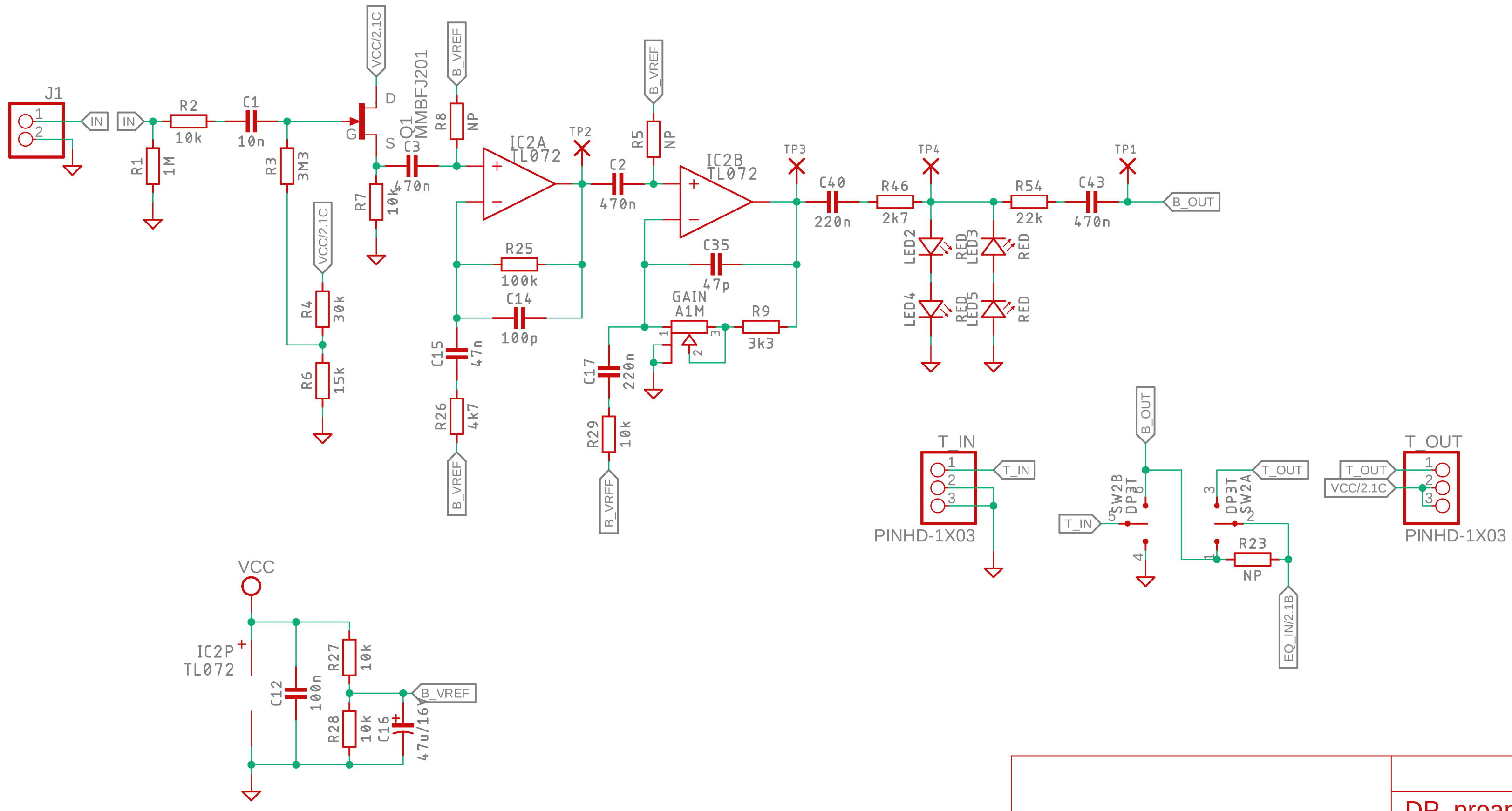

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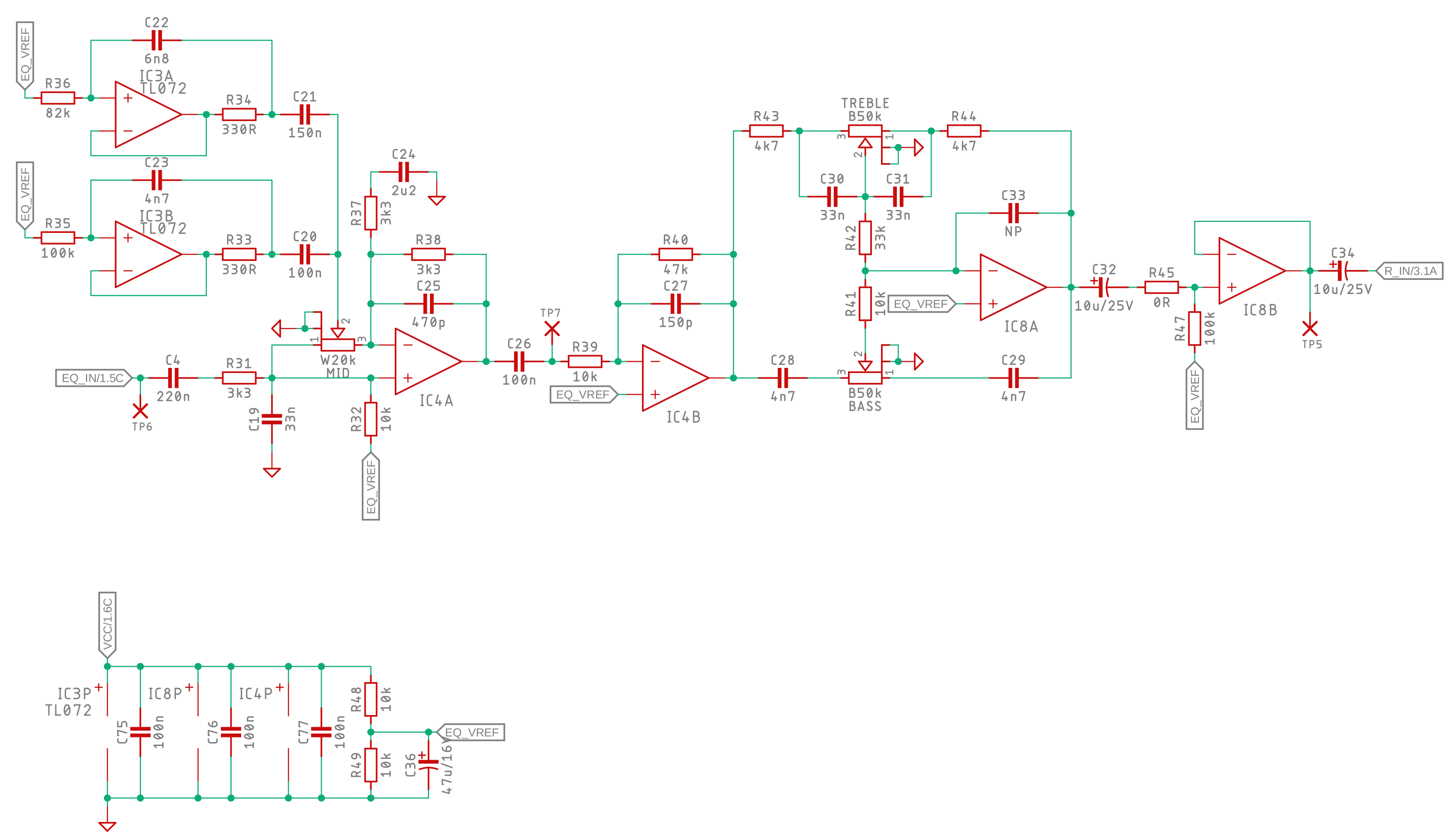

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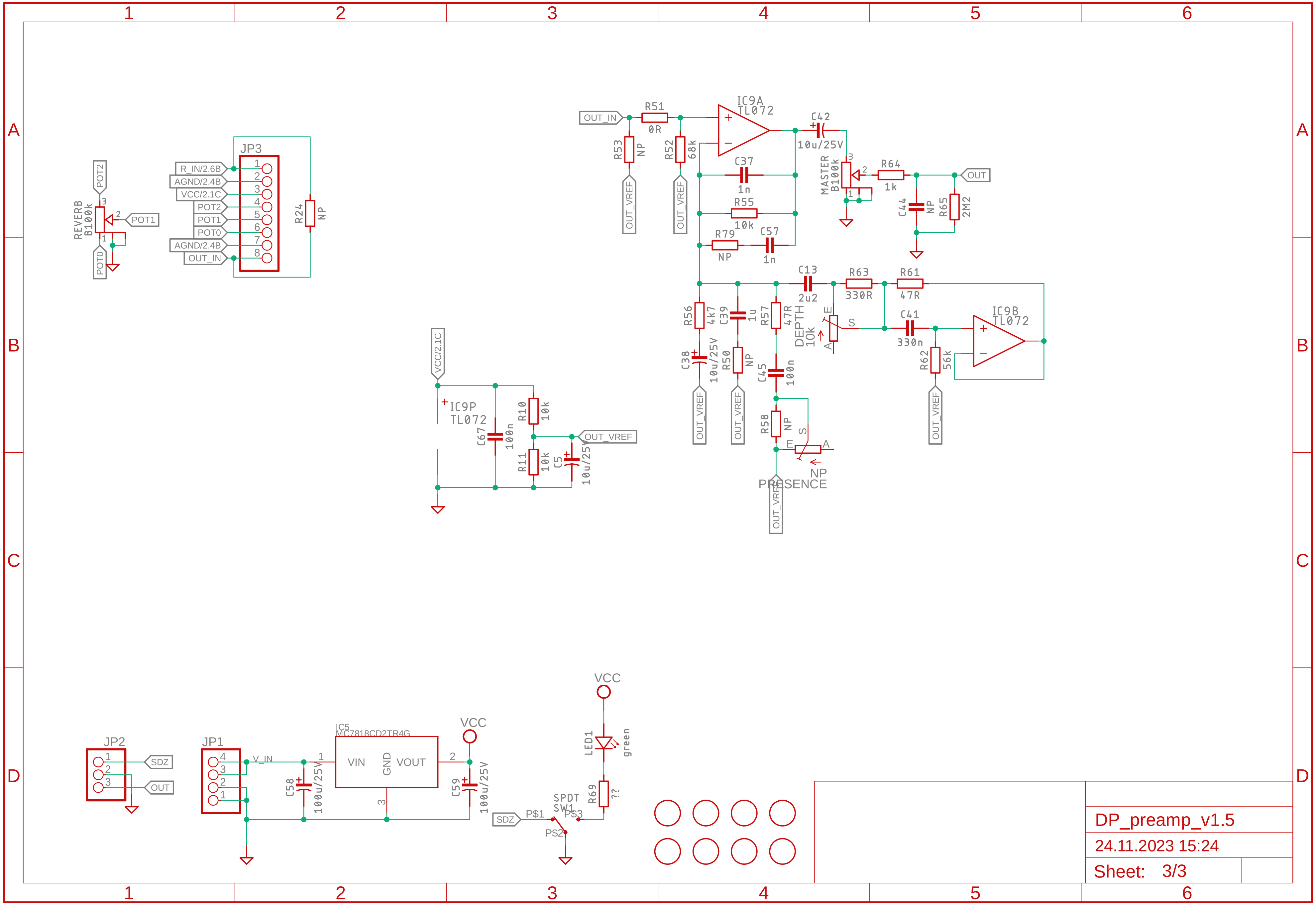

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IC9P TL072
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C42 10u/25V
C37 1n
R55 10k
R79 NP
C57 1n
MASTER B100k
R64 1k
C44 NP
R65 2M2
OUT
OUT_IN
OUT_VREF
C13 2u2
R63 330R
R61 47R
C41 330n
R62 56k
R56 4k7
C38 10u/25V
C39 1u
R50 NP
R57 47R
C45 100n
R58 NP
DEPTH 10k
NP PRESENCE
VCC/2.1C
R10 10k
R11 10k
C67 100n
C5 10u/25V
REVERB B100k
POT0
POT1
POT2
JP3
R_IN/2.6B
AGND/2.4B
VCC/2.1C
R24 NP
JP2
JP1
SDZ
V_IN
IC5 MC7818CD2TR4G
VIN
GND
VOUT
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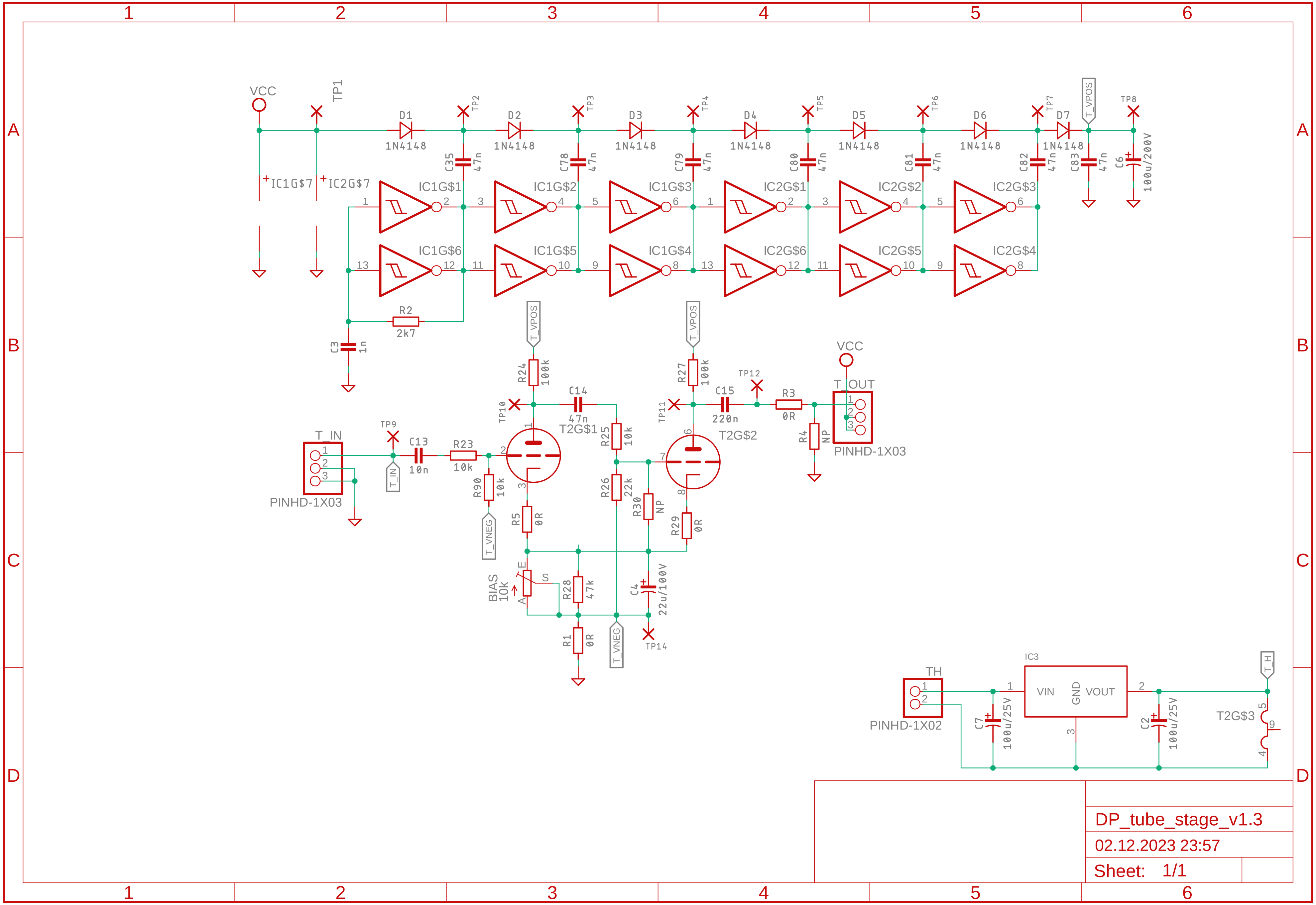
C59 100u/25V
VCC
LED1 green
R69 ??
SPDT SW1
P$1
P$2
P$3



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1N4148
TP2 TP3 TP4 TP5 TP6 TP7 TP8
T_VPOS
C35 C78 C79 C80 C81 C82 C83
47n
C6
100u/200V
IC1G$7 IC2G$7
IC1G$1 IC1G$2 IC1G$3 IC2G$1 IC2G$2 IC2G$3
IC1G$6 IC1G$5 IC1G$4 IC2G$6 IC2G$5 IC2G$4
R2
2k7
C3
1n
R24
100k
R27
100k
C14
47n
T2G$1
C15
220n
T2G$2
TP10 TP11 TP12
R3
0R
R4
NP
VCC
T_OUT
PINHD-1X03
T_IN
PINHD-1X03
TP9
C13
10n
R23
10k
R90
10k
T_VNEG
R25
10k
R26
22k
R30
NP
R5
0R
R29
0R
BIAS
10k
R28
47k
C4
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R1
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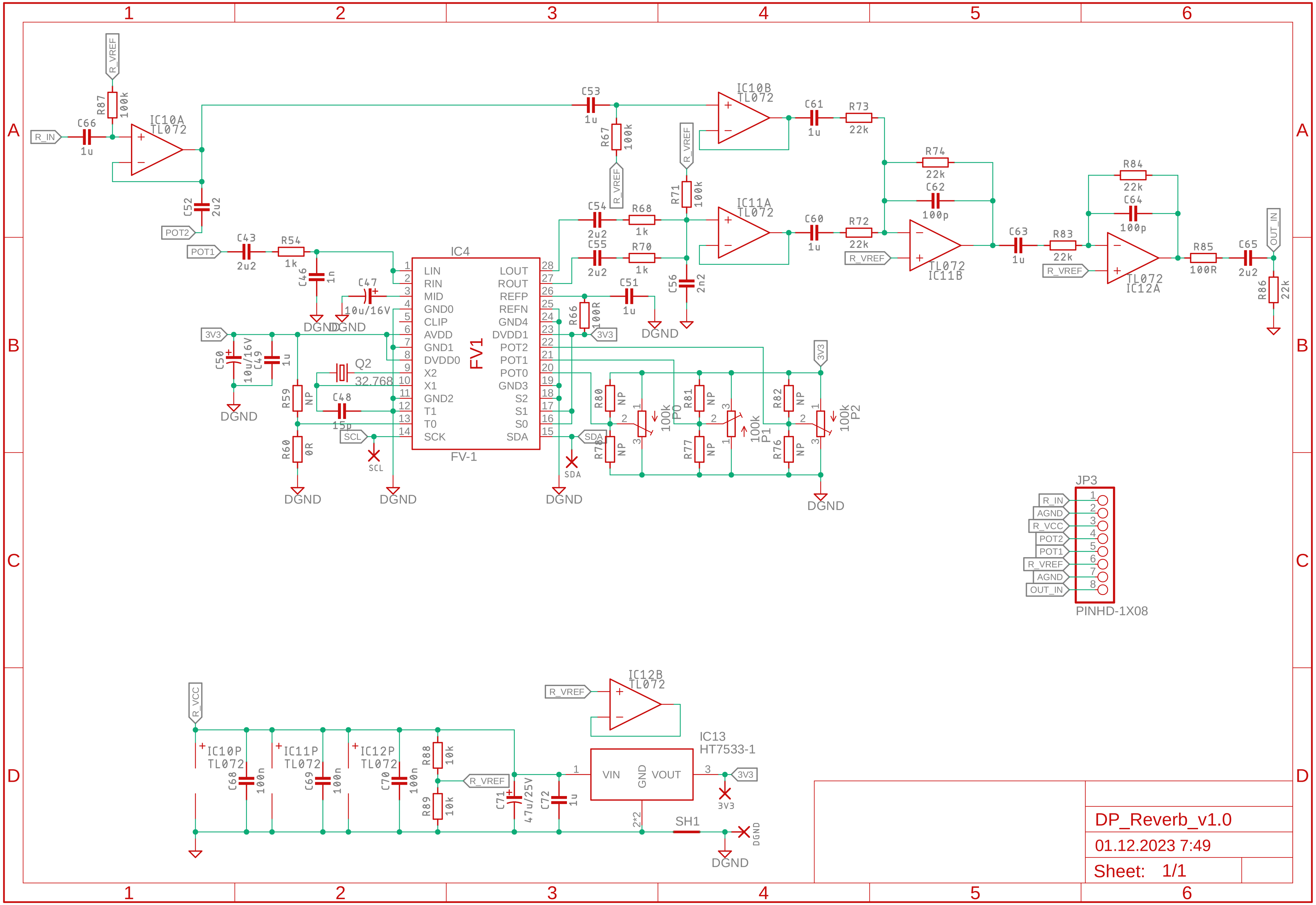

IC10A TL072
IC10B TL072
IC11A TL072
IC11B TL072
IC12A TL072
IC12B TL072
IC4
FV1
FV-1
LIN RIN MID GND0 CLIP AVDD GND1 DVDD0 X2 X1 GND2 T1 T0 SCK
LOUT ROUT REFP REFN GND4 DVDD1 POT2 POT1 POT0 GND3 S2 S1 S0 SDA
Q2 32.768
P0 100k
P1 100k
P2 100k
JP3
PINHD-1X08
R_IN AGND R_VCC POT2 POT1 R_VREF AGND OUT_IN
IC13 HT7533-1
VIN GND VOUT
SH1
IC10P TL072
IC11P TL072
IC12P TL072
R_VREF
3V3
DGND
SCL
SDA
DP_Reverb_v1.0
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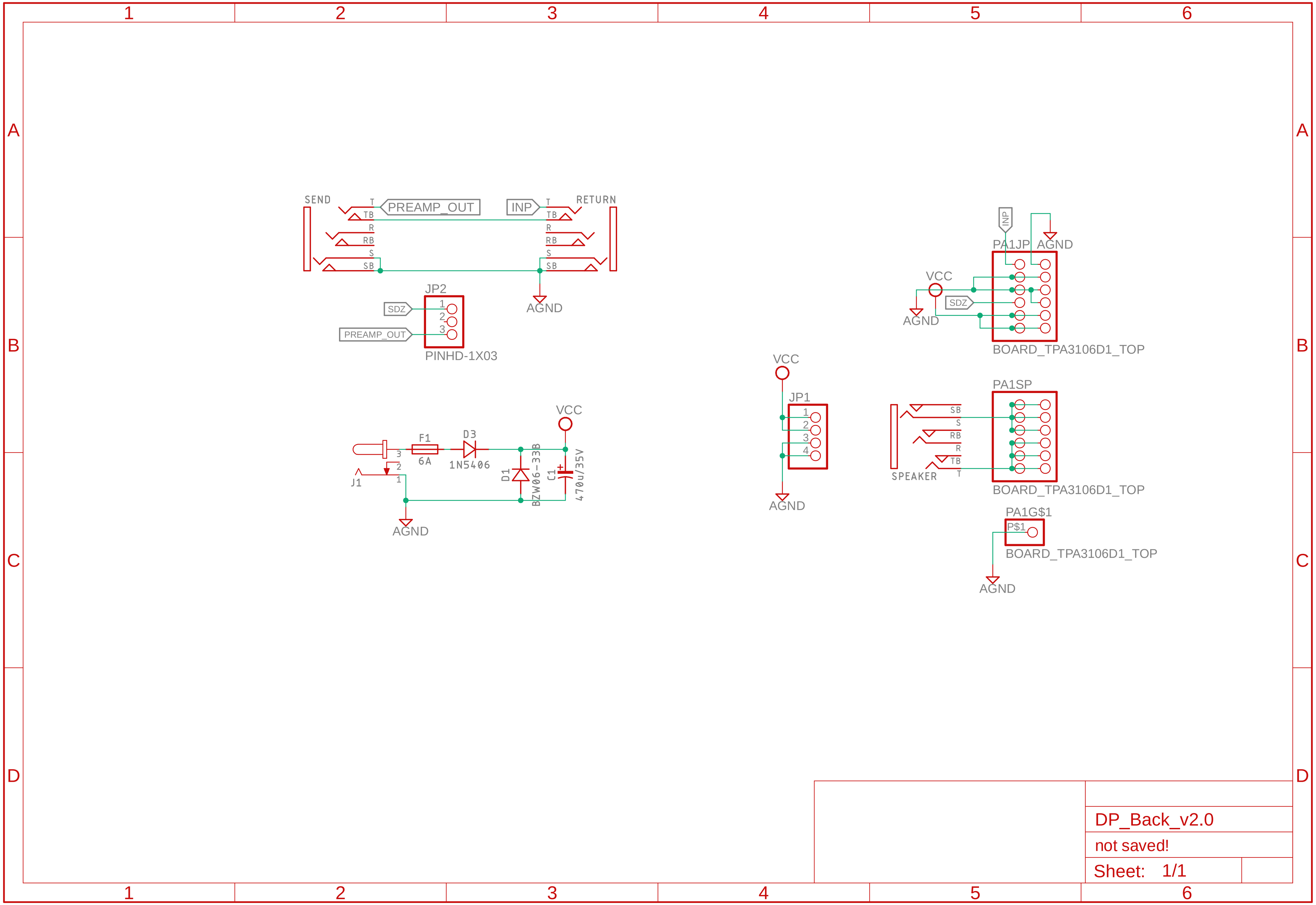
Sheet: 1/1



1
2
3
4
5
6
A
B
C
D
SEND
PREAMP_OUT
INP
RETURN
T
TB
R
RB
S
SB
JP2
SDZ
PREAMP_OUT
PINHD-1X03
AGND
F1
6A
D3
1N5406
D1
BZW06-33B
C1
470u/35V
VCC
J1
AGND
VCC
JP1
AGND
PA1JP
INP
AGND
VCC
SDZ
BOARD_TPA3106D1_TOP
PA1SP
SPEAKER
BOARD_TPA3106D1_TOP
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P$1
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AGND
DP_Back_v2.0
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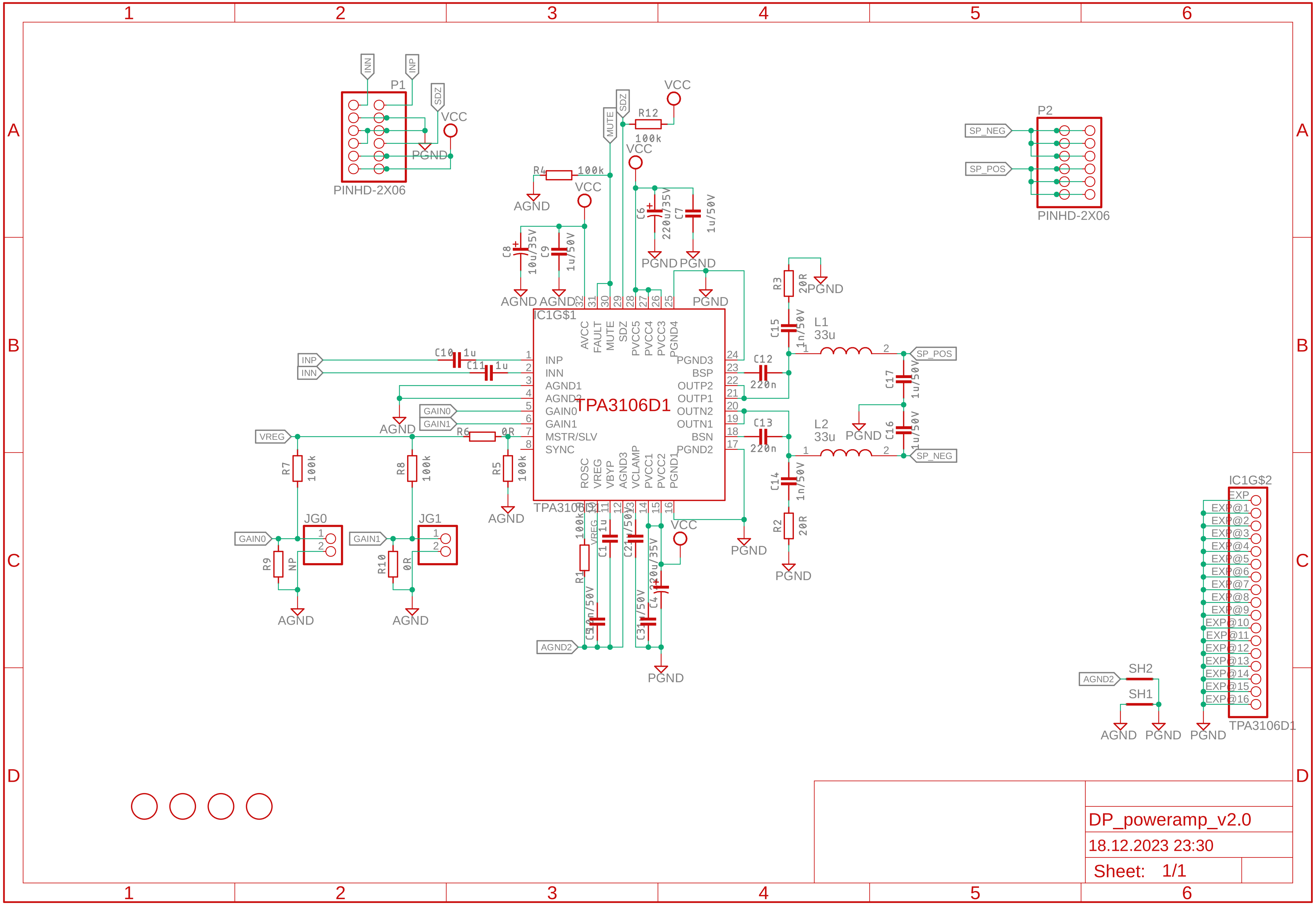
Sheet: 1/1



TPA3106D1
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P1
P2
PINHD-2X06
JG0
JG1
SH1
SH2
L1 33u
L2 33u
VCC
AGND
PGND
AGND2
INP
INN
SDZ
MUTE
VREG
GAIN0
GAIN1
SP_POS
SP_NEG
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Appendix A

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