HYBRID AMP - LIMITED EDITION

Joost Breed – May 2024

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Specifications

- Tube (ECC88) pre-amplifier
- Dual-MOSFET class AB power amplifiers
- Exicon ECX10N20 and ECX10P20 lateral MOSFETs
- No negative feedback used
- Input sensitivity: 1.037 V (80 W @ 8 Ω)
- Max. power: 80 W @ 8 Ω / 160 W @ 4 Ω
- THD: 0.015 % @ 1W / 8 Ω
- THD: 0.2 % @ 50W / 8 Ω
- Bandwidth: 4Hz – 120kHz
- Amplifier Gain: 56
- Output impedance: 0.4 Ω
- Damping factor: 20 @ 8 Ω

Features

- Baxandall bass / treble tone control
- Tone control bypass relays
- Low bias / high bias selector
- IR remote control
- Motorized and buffered volume control
- 4 selectable source inputs
- Dual speaker output selectors (A, B, A+B)
- DC output correction
- Delayed power-on output switching
- Output protection with DC-detection
- Heatsink temperature protection with automatic shutdown
- Automatic standby when no audio detected
- Switched Mode Power Supply
- VU-meters
- ESP32 Microcontroller
- Less capacitors in the audio path
- Use of a symmetrical power supply

The project

In 2022 we at TubeSociety designed an amplifier consisting of a tube preamplifier and a mosfet power amplifier. This design was a huge success and was successfully made by several TubeSociety students with excellent results. It has 30W (8Ω) output power and sounded very well.

A colleague of mine wanted to build the 2022 project. Then I got the idea to make a slightly more advanced version with further improvements and several extra features like the ones that can be found in amplifiers that you can buy at the hi-fi shop. The amplifier should also look like that. My colleague designed a beautiful casing for it in Autodesk Inventor.

Original project – TubeSociety OTL-2022

Below the schematics of the original TubeSociety project made by the students in 2022 for comparison.

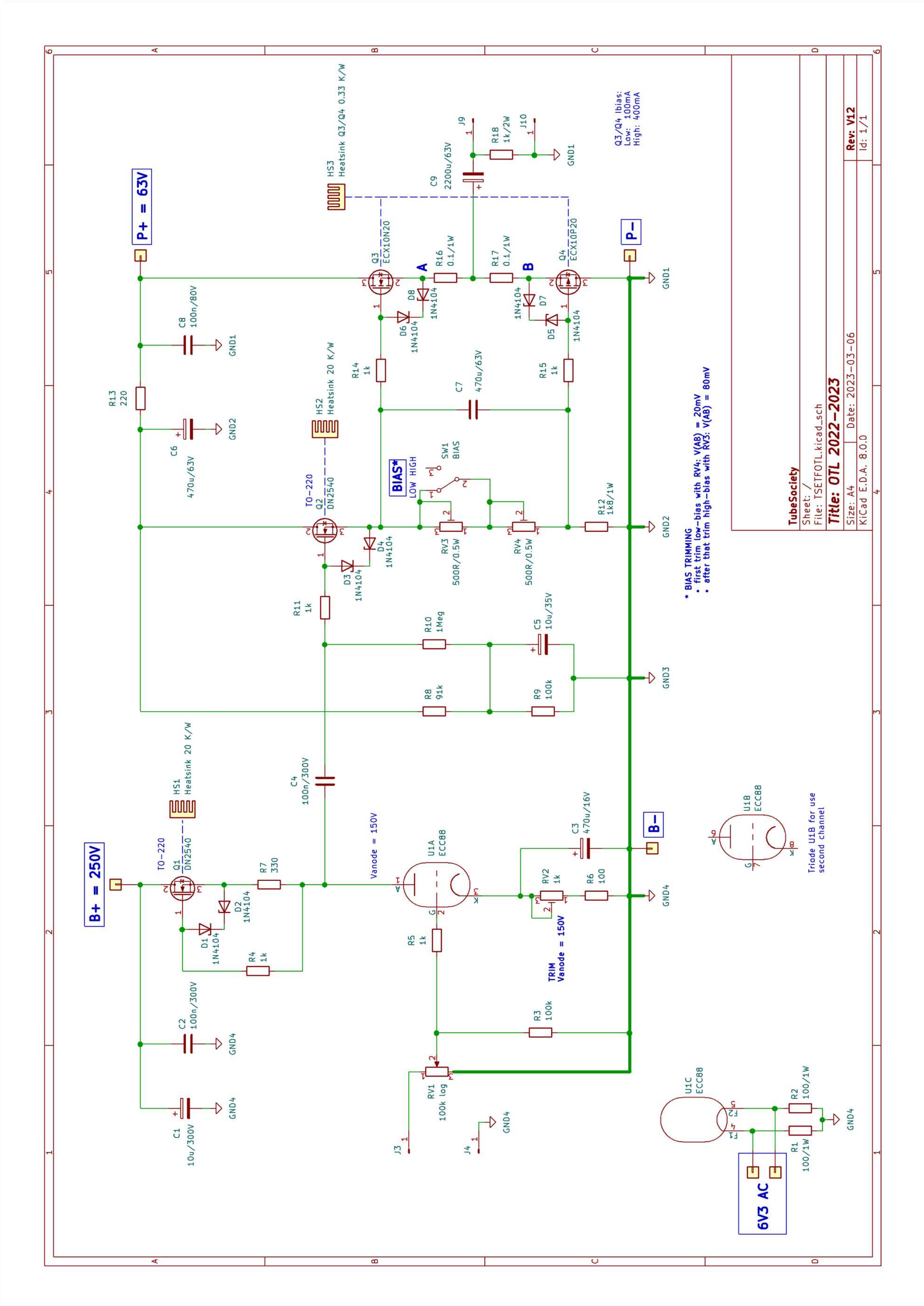


Figure 1 - 2022 project schematics

The new design

The new amplifier design consists of several schematics and a total of seven separate PCBs were designed. The schematics of each of those can be found below and are explained in this chapter.

Input selection

The input selection [Figure 4] has a relay for each source input. Each relay is switched by an N-channel mosfet. These mosfets are driven by the microcontroller on the front panel pcb. Each relay has a diode to protect it from back-EMF when the coil is switched off.

Volume control

The volume is controlled by a motorized ALPS potentiometer [Figure 5]. The input and output of the potentiometer are buffered by OPA1656 opamps. This way the potentiometer is isolated and not loaded for better performance. The gain of the opamps after the potentiometer is set to 1, but can be changed with resistors R27, R29 to match the output levels of the left and right channel. This difference is caused by the triode halves which are not identical. In my case the difference was 0.9 dB. I added a 39 kΩ resistor in parallel of R29 to make the levels equal within 0.1 dB.

Capacitor C10 at the input of opamp U4 is there to block any dc component from the device attached to the input. Resistor R25 determines the input impedance. This is set to 47 kΩ. Both C10 and R25 form a passive high-pass filter. We want this filter to be well below the audio range, around 1Hz. So the capacitor needs to be C = 1 / (2* π*R*f) = 1 / (2* π*47k*1) = 3.4 μF. We take 3.3 μF.

Tone control

The tone control is a standard Baxandall type bass and treble control circuit which I copied from Douglas Self's excellent book 'Small Signal Audio Design'. The tone control can be bypassed by relay K3 which is controlled by the microcontroller via a mosfet.

Preamplifier

The preamplifier [Figure 6] uses a single ECC88 tube for both channels. The tube is bootstrapped to get maximum gain and the least distortion possible.

Zener diodes are used to generate a 235 V to dc-bias the mosfet. The current through the Zener diodes is 1.4 mA. A 300V power supply is used so resistor R76 needs to be (300-235) V / 1.4 mA = 46.4 kΩ. A capacitor of 22 μF (C48) is used to stabilize the Zener voltage. The gate-source voltage of the mosfet is 5 V, so top side of the anode resistor is always 5 V lower than the Zener voltage.

I've selected an anode voltage of 140 V and an anode current of 5mA. The value of R48 must then be (230V – 140V) / 5 mA = 18 kΩ. The gate is biased at -3 V, the drain current is the same as the anode current. The source resistor value must therefore be 3 V / 5 mA = 600 Ω. We will take a standard value of 560 Ω. Grid resistor R50 is added to prevent high frequency oscillations. Resistor R83 is used to prevent loud clicks when the tone control bias relays is being switched. In the first design I omitted this resistor, but without that resistor the grid voltage rises to about 4V for a period of 200 us when switching the tone control bypass relay because the relay output is floating while the relay switches. This causes a 40V spike at the speaker output resulting in a loud bang from the speaker. Now a 1 M Ω resistor keeps the voltage referenced to ground when the relays are switching. Capacitor C49 is used to block the 140V dc to the power amplifier.

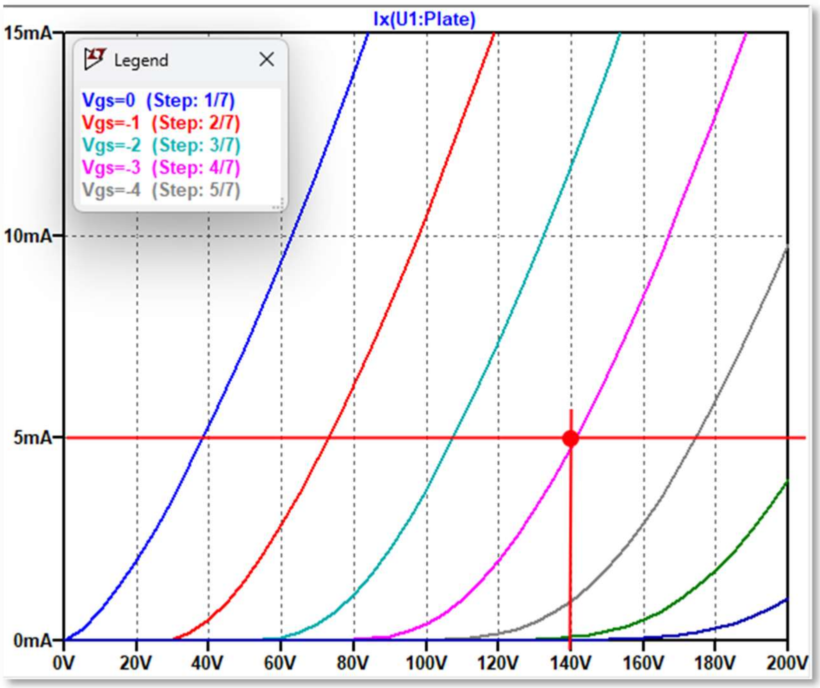


Figure 2 - Preamp bias point

Bootstrapping

The capacitor between the anode and the base of the mosfet is a short for ac signals (audio). Therefore the gate of the mosfet will also see this ac signal. The source of the mosfet follows the gate, this results in the source of the mosfet also being changed by the same amount as the anode of the tube. So when the anode voltage rises, the voltage at the top-side of the anode resistor (R48) also rises with the same amount. This means that the voltage across R48 does not change and therefore the current through the resistor will always be the same during a whole cycle. We've created a current source.

The impedance the tube is seeing at the anode is the difference in anode voltage divided by the difference in the anode current. So the impedance the tube is seeing is $Z = \delta v / \delta i$. But since δi does not change the impedance goes to infinity. In reality it does change a little bit because we do not have ideal components.

In the simulation with an exact model of our tube and mosfet we can see: $Z = 65\ V / 44\ uA = 1.48\ M\Omega$.

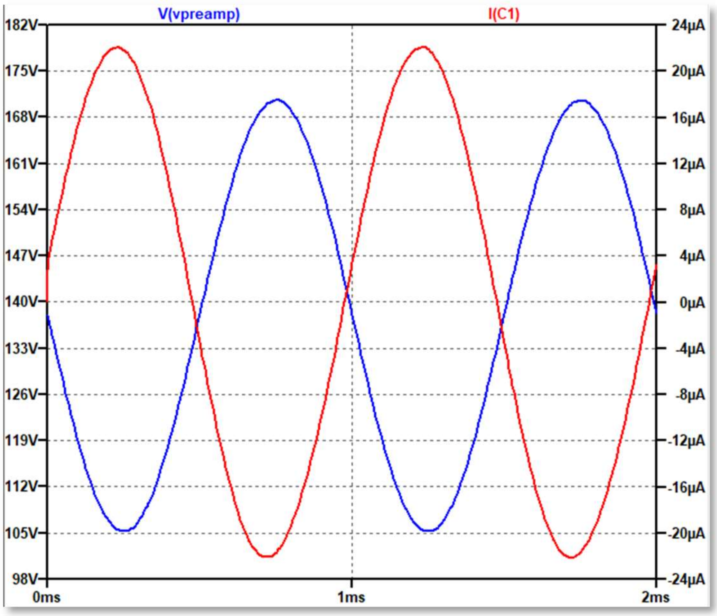


Figure 3 - LTSpice simulation

The advantage of the bootstrapping method is that we get the maximum voltage amplification of the tube, which is equal to μ=33. Also the amplification is constant over the complete voltage range so we get less distortion. The downside is that a higher supply voltage is needed to accommodate the voltage change at the source of the mosfet. This extra voltage must be the same as the maximum output voltage which is about 65 V. The power supply needs to be 235 V + 65 V = 300 V.

Because of the bootstrapping a bypass capacitor in parallel of the cathode resistor has little effect, so it has been removed to get a better frequency response.

Power amplifier

If you look through your eyelashes to both the old and the new amplifier schematics [Figure 7] you will see a lot of similarities with the original TS-2022-OTL amplifier, but a lot of changes have been made which greatly increases the complexity and component count and pcb size as well.

The input of the power amplifier is connected to the gate of a source-follower made with Q2. D2 and D3 protect the mosfet against overvoltage. The current through Q2 is made constant with a current source created with Q4 and R9. This current is set to 15mA. R6 is there to prevent oscillations.

Q3, Q5, R3, R8, R5, RV1 and RV2 form a bias-spreader which creates the bias voltage for the power mosfets. Relay K1 is used to switch between low-bias and high-bias. Low-bias is used when listening to the amplifier in the background. The distortion will be around 0.27 %. When you like to listen to music with less distortion (0.015 %) the amplifier can be set to high-bias mode. The current through the power mosfets will be 45mA when set in low-bias and 200mA when set in high-bias. Because of that the power consumption is much greater in high-bias mode. This will also result in a temperature rise of the heatsinks.

C6 is used as a bypass capacitor for the audio signal. Zender diodes D4 and D7 are there to limit the current and protect the gates of Q8-Q11. R11 and R12 reverse-bias the Zener diodes to reduce their capacitance.

Q6 and Q7 are emitter-followers used to drive the power mosfets. A current of about 20mA flows through these transistors, enough to drive the mosfet capacitance. This current is set by R13 and R14.

The power mosfets are in a push-pull arrangement. These mosfets, made by Exicon, are specifically designed for linear audio applications. The Exicon mosfets can dissipate up to 125 W each when cooled sufficiently. The channel temperature may reach a maximum of 150 °C.

One major difference compared to the previous design is the use of a symmetrical power rail. It uses a +/- 40 V dual-rail power supply instead of a +63V single-rail supply. This has the advantage of being able to take out the large coupling capacitor of 2200 µF out of the audio path. This means that the speaker will be directly connected to the amplifier output.

Since we do not want the speaker to see any dc-component a dc-servo circuit had to be added to the design. This dc-servo is a negative feedback loop between the output and the input of the amplifier. An integrator circuit made around U1, R14 and C7 has been put in that feedback loop. The output of this integrator is filtered by a low-pass filter of 0.5 Hz (R10 and C3) before it is fed back to the input of the amplifier. Diodes D8 and D9 limit the input voltage of the integrator to 0.7 V. Resistor R14 limits the current in the case the diodes conduct. Any dc-component at the output of the amplifier will result in an opposite voltage being injected by the dc-servo at the input of the amplifier. This closed-loop system will ultimately result in a dc-component of a few µV at the speaker output. The time constant is about 2 s, so it will take a little while to stabilize when the amplifier is turned on. A dc protection circuit will prevent the speaker to be connected to the amplifier when the dc voltage becomes too high.

The power supply voltage is buffered by capacitors C14-C21. Some 100 nF capacitors are used to decouple the power supply preventing noise and oscillations. Diodes D10-D13 protect the amplifier against voltages with the wrong polarity.

The Zobel network R35, C25 is included to keep the amplifier from becoming unstable under unusual load conditions. It prevents the amplifier to oscillate at higher frequencies when no load is attached. The network becomes resistive at high frequencies reducing the damping factor therefore reducing the high frequency response.

The speaker protection circuit [Figure 11] is an adapted copy of the one used by the Elektor Fortissimo-100 amplifier. It consists of a power supply detection, switch-on delay and a dc-detection and protection circuit. If the 40 V power supply is present and no dc component is detected at the amplifier output the speaker relay is switched.

Microcontroller

An Espressif ESP32 microcontroller [Figure 8] running at 240 MHz is used to control the amplifier. It reads the buttons, switches the relays, reads the infrared sensor, controls the volume control motor, reads heatsink temperatures and detects if any audio is present. Software is kept simple and is written in the Arduino platform.

Although it can be done in software, all buttons are debounced with a low pass filter network. All LEDs are switched by small mosfets because the ESP32 is not capable of driving a lot of LEDs at the same time.

The microcontroller measures the heatsink temperature with digital sensors. When the temperature of one or both of the heatsinks becomes too high the amplifier will disable high-bias mode if enabled. If the temperature still rises a few degrees the amplifier will be shut-off.

The audio activity monitor detects any audio at the input and converts it in a positive pulsing voltage which is safe to connect to the adc input of the microcontroller. If no audio is detected by the microcontroller for 10 minutes the amplifier will go to stand-by mode.

A 230 Vac to 5 Vdc converter is used to create the supply voltage of some relays and the 3.3 V supply voltage for the microcontroller. This power supply will always be powered. This way the IR remote can be used to switch on the amplifier. The amplifier will only draw a few mW when in stand-by mode because the switching power supply and the transformer are switched off completely.

VU meter circuit

I came across a nice and simple VU-meter circuit [Figure 10] on the website Elliot Sound Products. It doesn't have to be calibrated, its only there for aesthetics. It could also be changed to a PPM meter. Although PPM meter is more useful and a VU meter almost useless the VU meter is chosen for vintage reasons.

Speaker outputs

The amplifier has two speaker outputs, A and B [Figure 12]. Either one or both of them can be switched on. Switching them both on at the same time will result in connecting speakers in parallel. This of course will affect the damping factor, but with high-bias enabled the output impedance of this amplifier is only 0.4 Ω.

Volume motor control

The volume motor control [Figure 13] is a logarithmic motorized ALPS potentiometer. Mosfets are used to switch on the motor and change the polarity through the motor which changes the direction it runs making the volume go up or down. This will happen if the IR remote control is used to change the volume.

Power supplies

To create the 300 Vdc voltage a small transformer is used [Figure 15]. The 230 Vac is rectified to 322 Vdc. A low pass filter with a source follower is used to get rid of most of the noise. It also acts as a slow start for the tube since it will take a few seconds to get the output voltage to the desired voltage because of the large time constant.

The transformer also has a 6.3 Vac output. 15 extra turns are added to the winding to increase the voltage to 8.3 Vac and 9.4 Vdc after rectification. This dc-voltage is high enough for linear voltage regulator U2 to create a stable and very low noise 6.3 Vdc for the tube filaments.

An 800 W switched-mode power supply is used to create the +/- 40 Vdc voltage rails for the power amplifier and the +/-15 V supply voltage rails used by the several opamps. R9-R12 are 0.1 Ω resistors used to measure the current to the amplifier when setting the amplifier bias. Seven fuses are used to protect the amplifier and power supplies.

Relay K1 switches the amplifier on or off and is controlled by the microcontroller which has its own power supply. This way a stand-by mode is created.

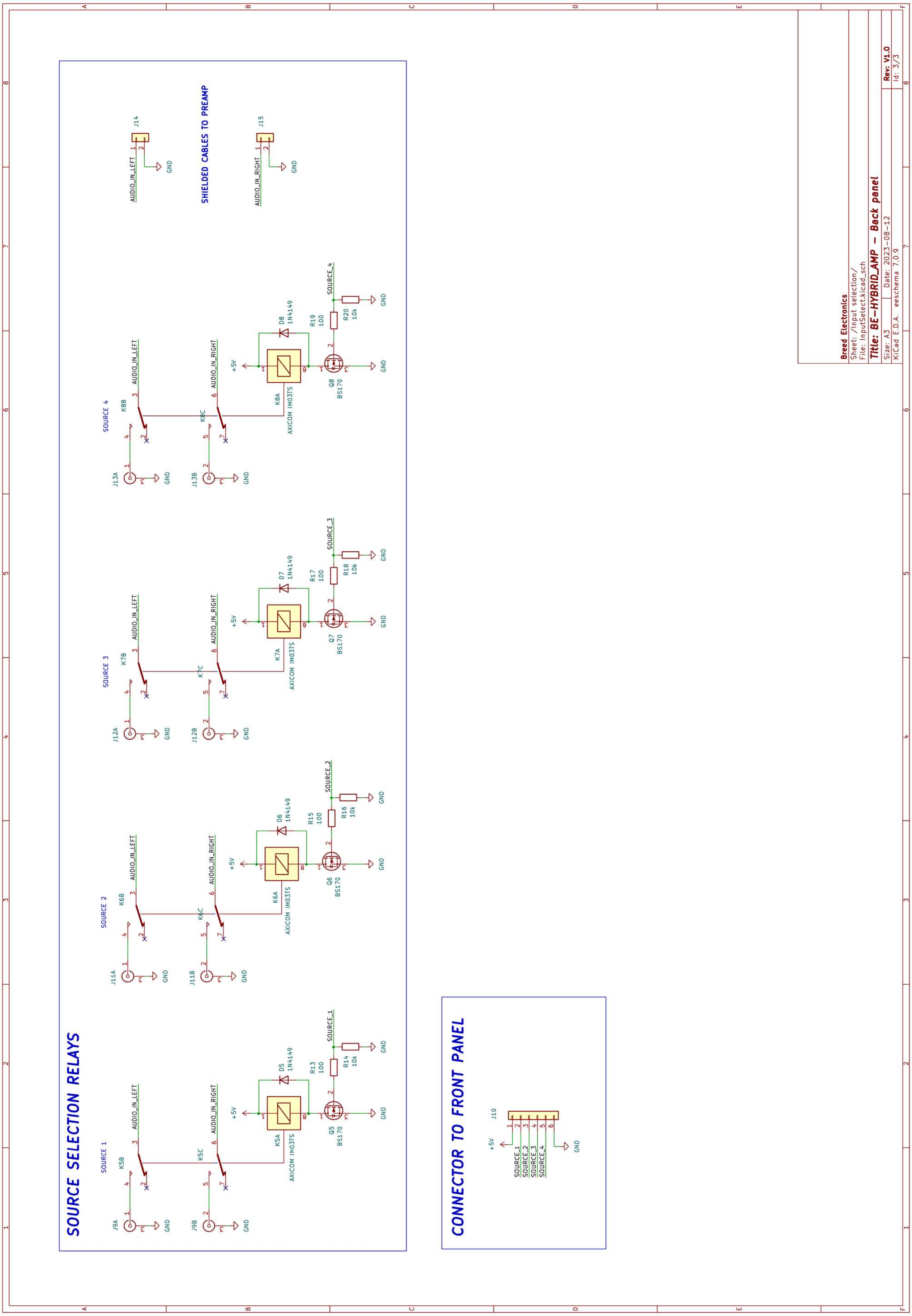


Figure 4 - Audio input section

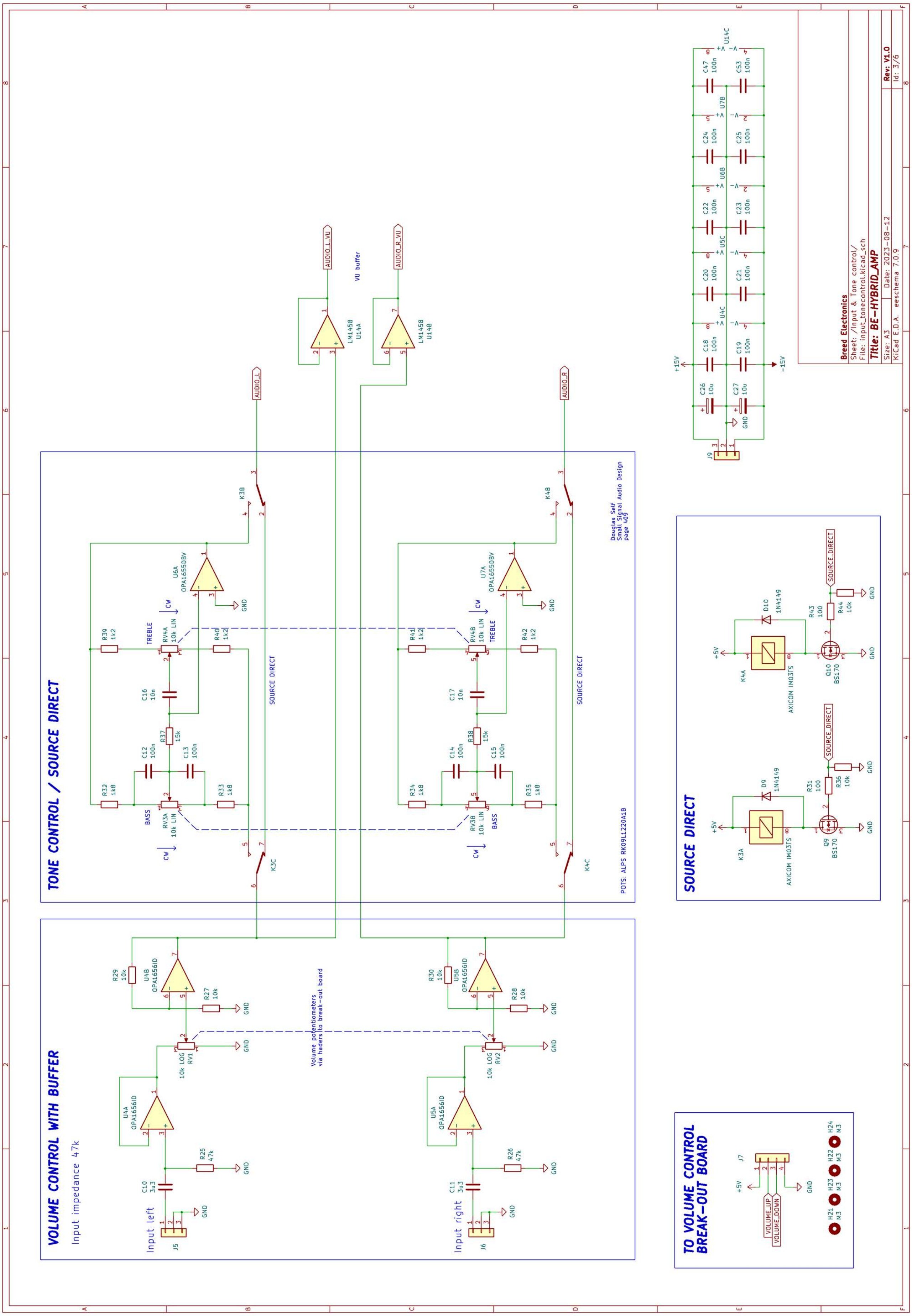


Figure 5 - Volume and tone control

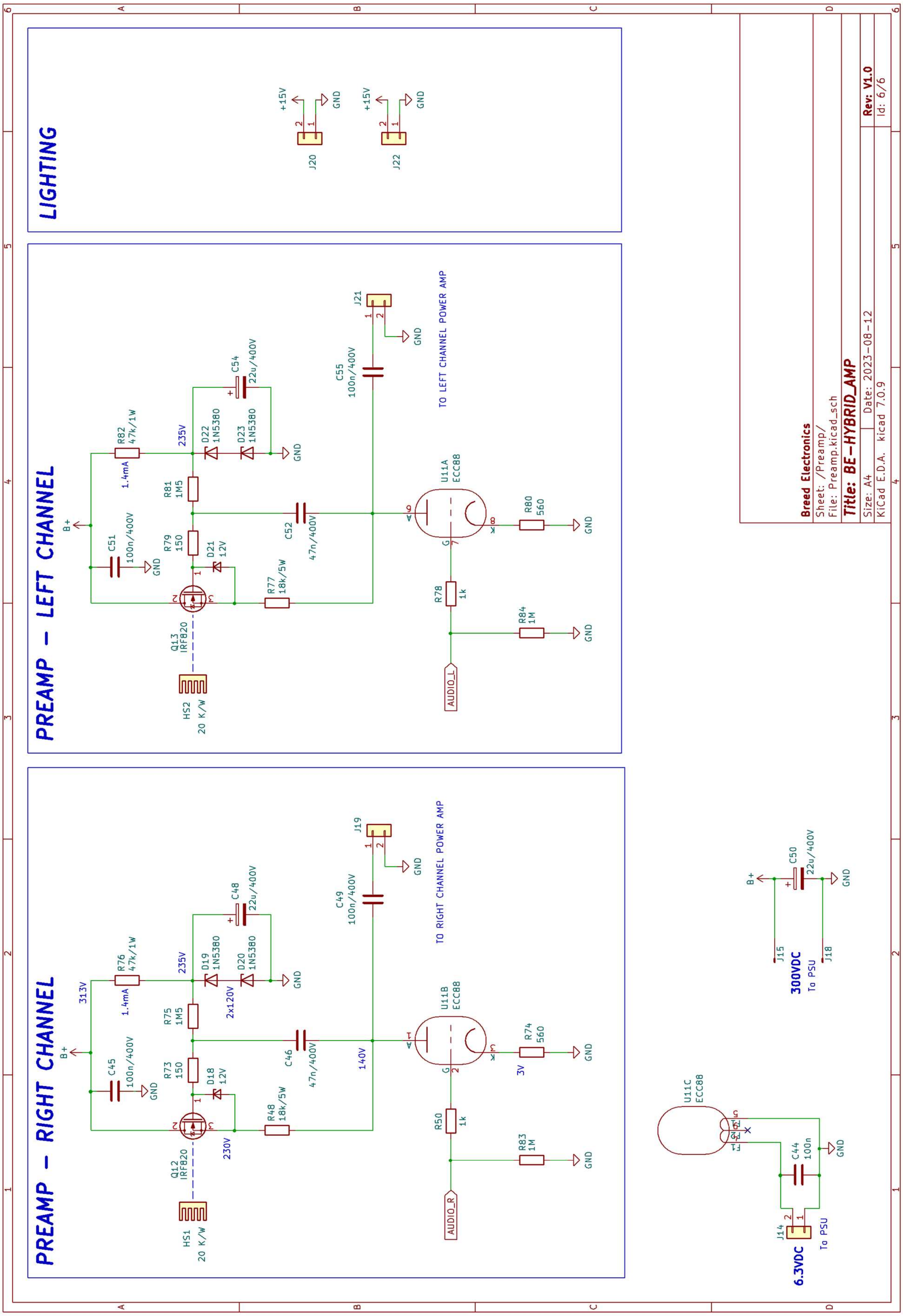


Figure 6 - Tube preamplifier

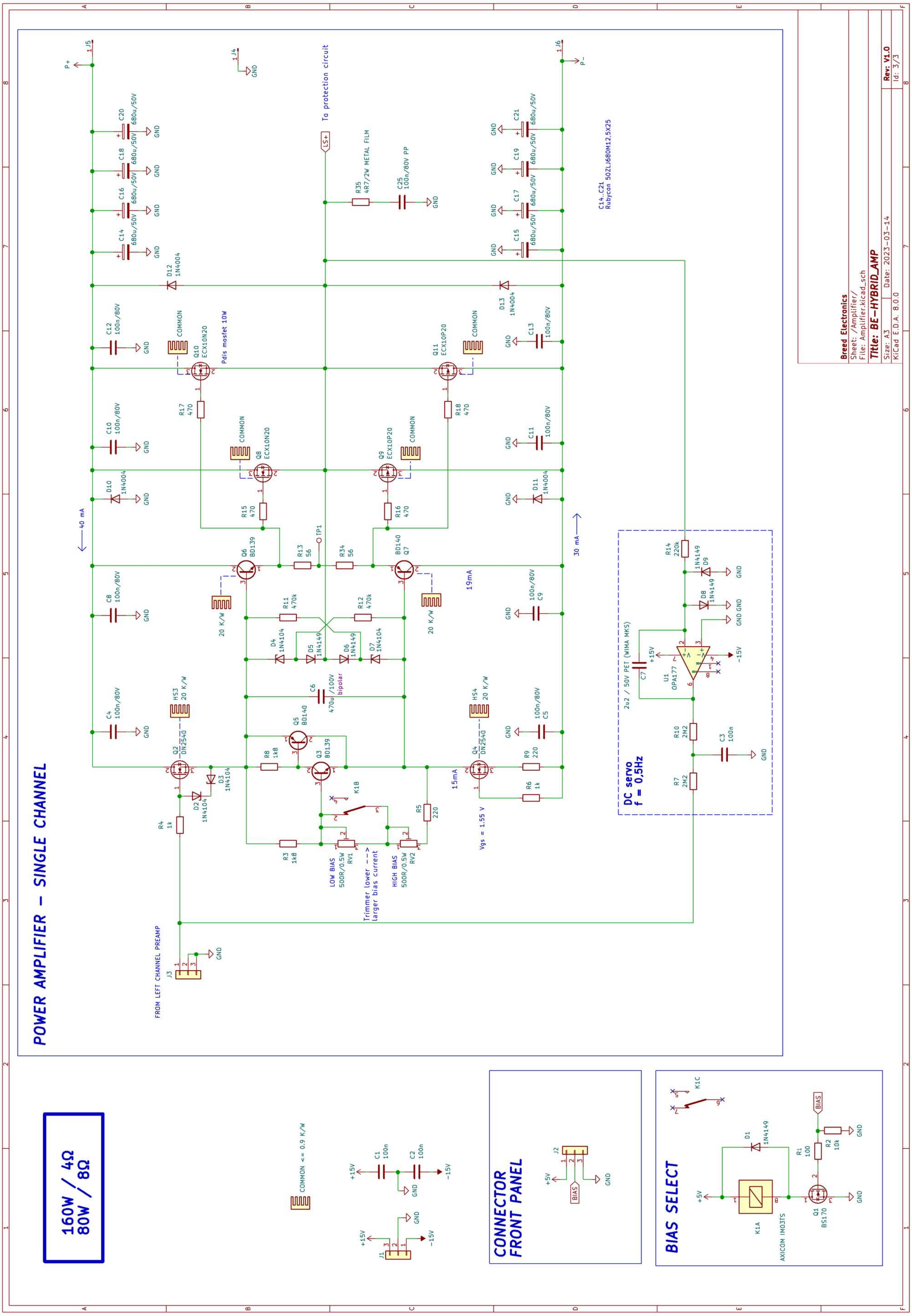


Figure 7 - Power amplifier, single channel

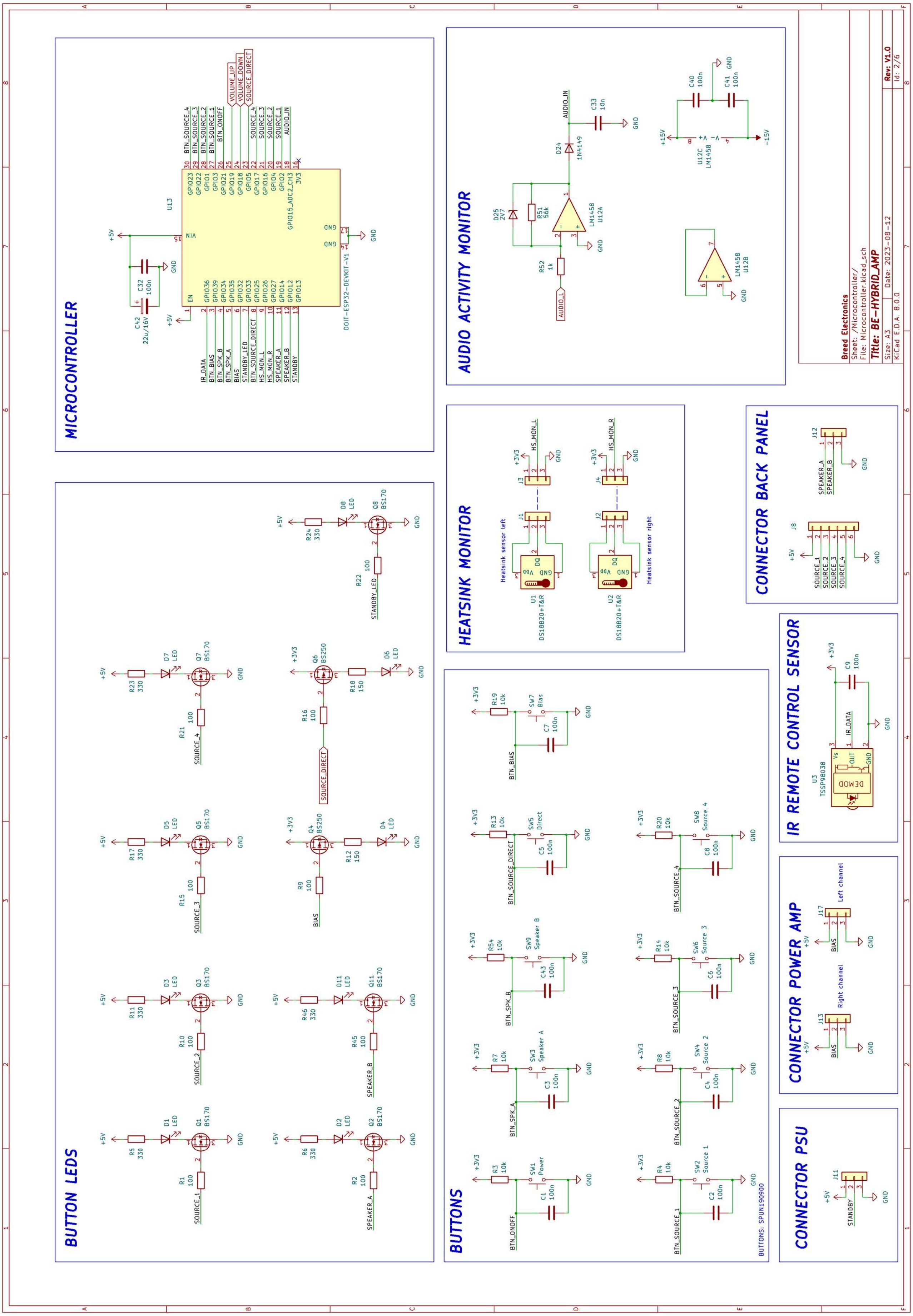


Figure 8 - Microcontroller and buttons

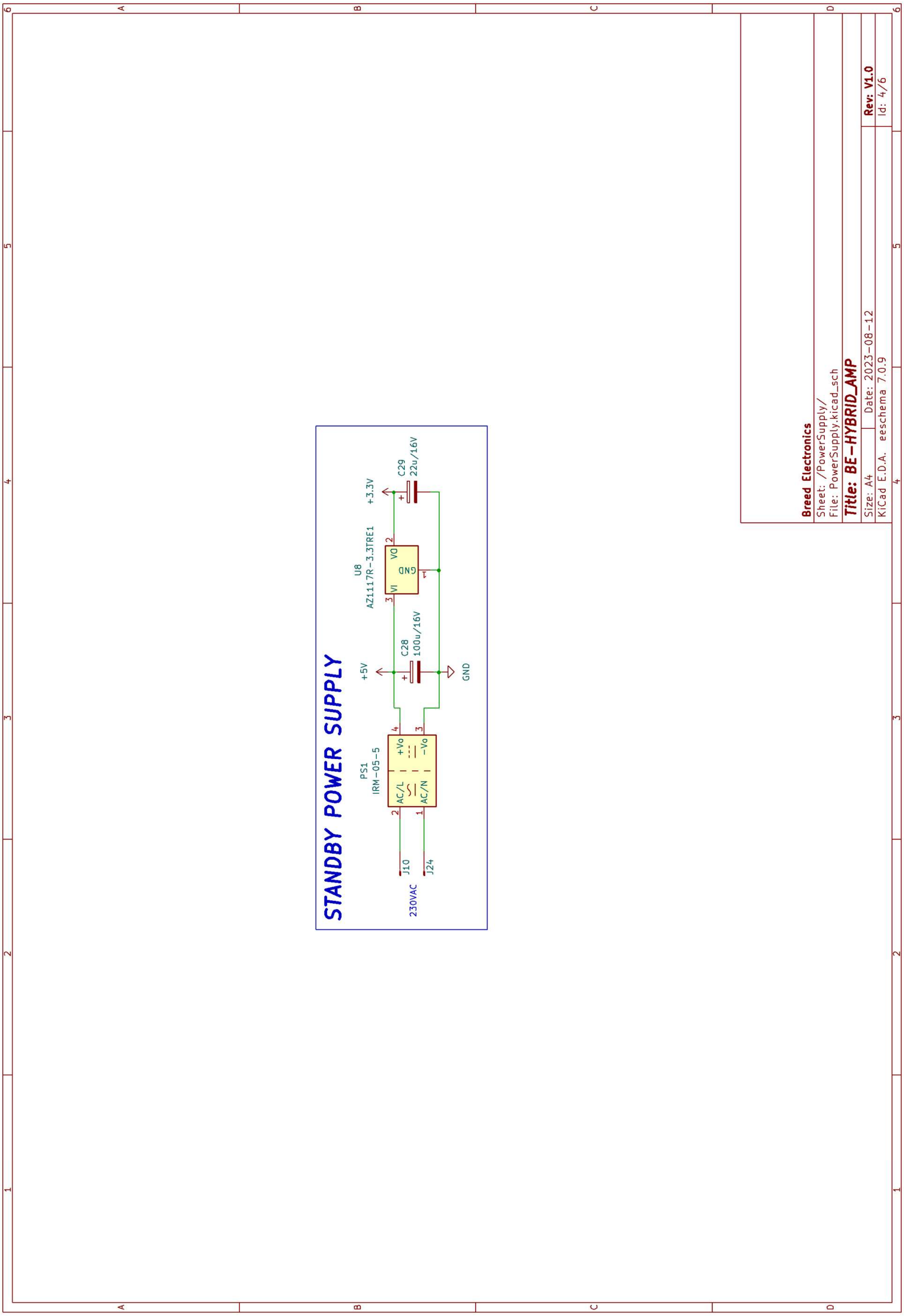


Figure 9 - Stand-by power supply

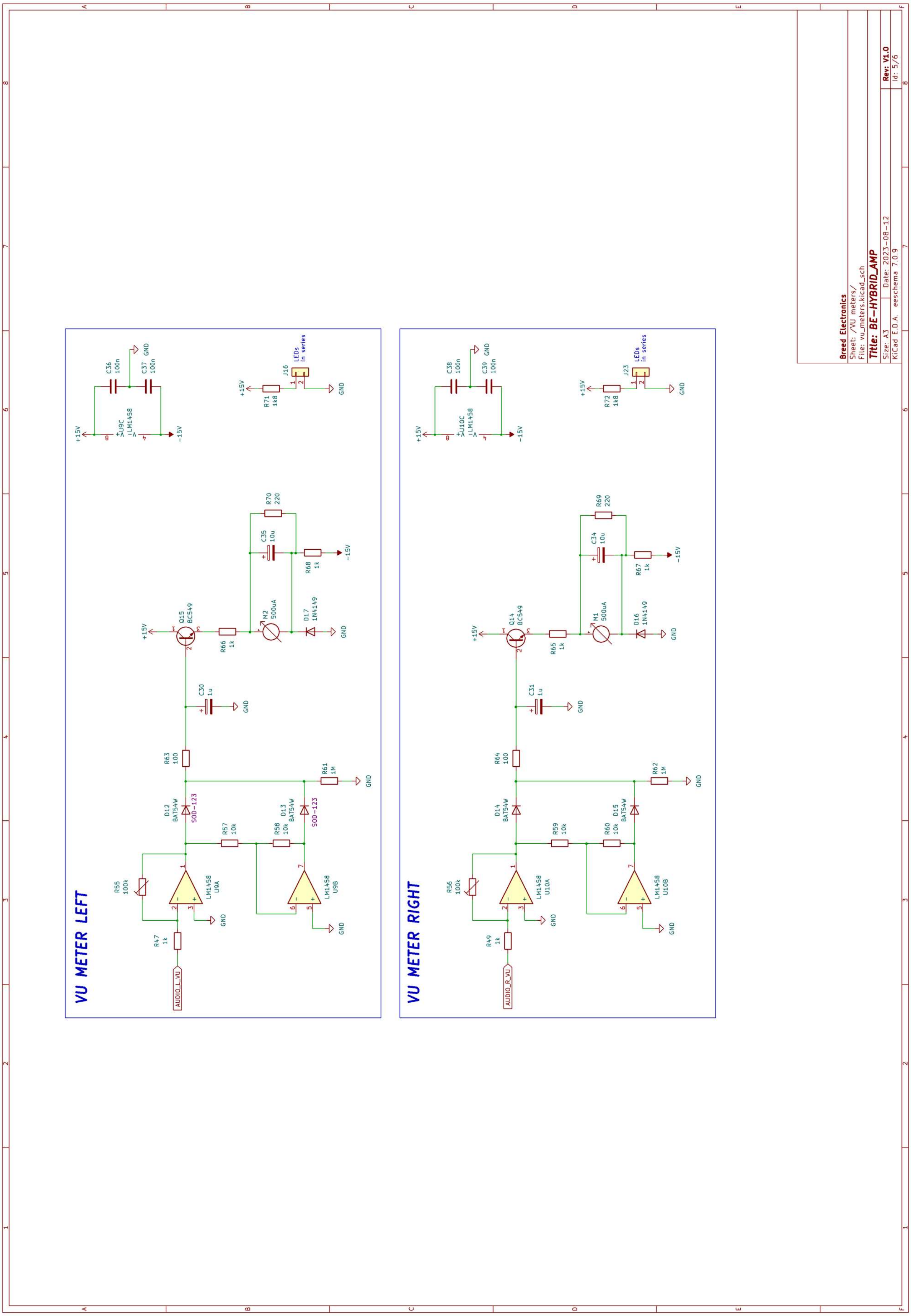


Figure 10 - VU meters

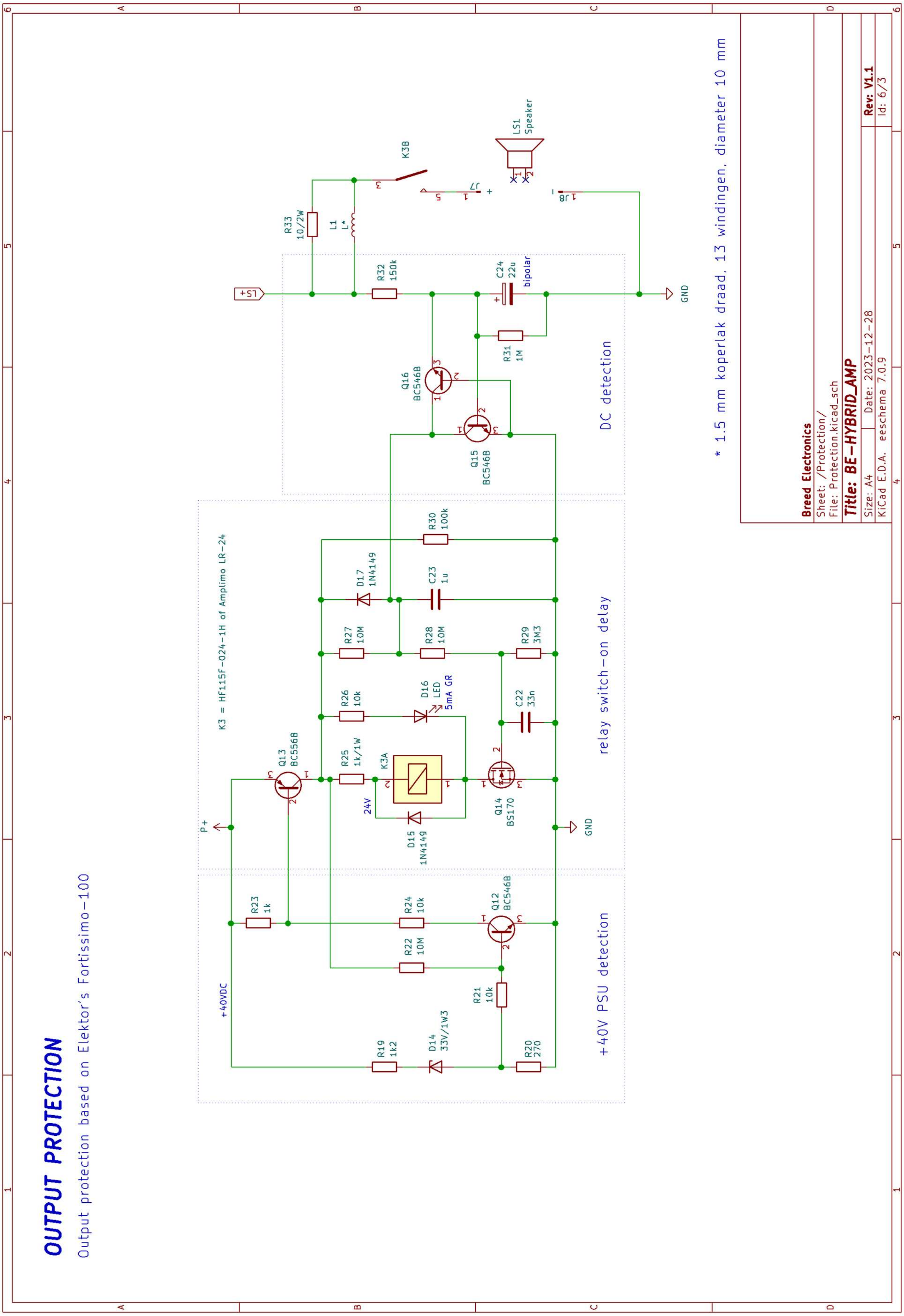


Figure 11 - Protection circuit, single channel

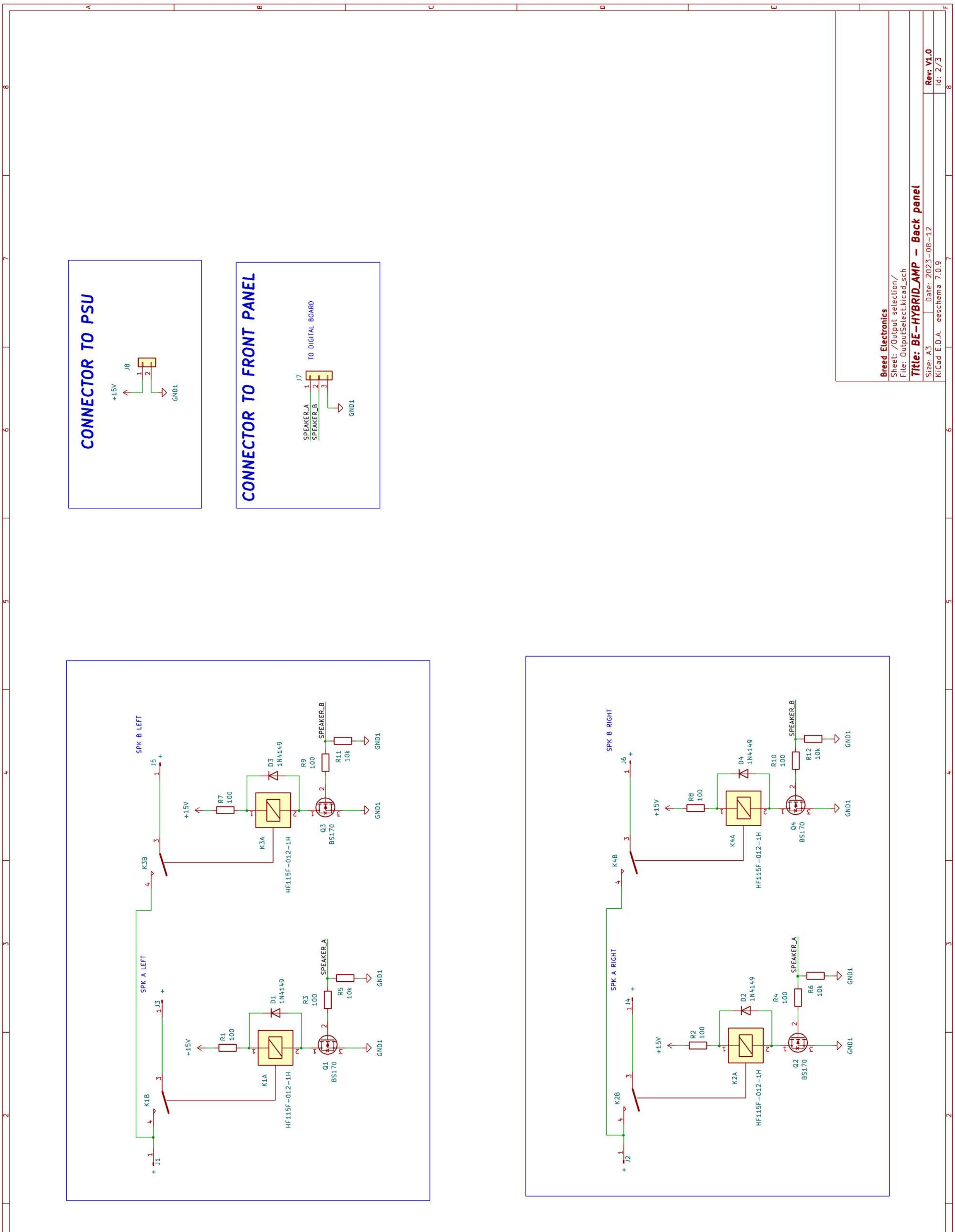


Figure 12 - Speaker selection

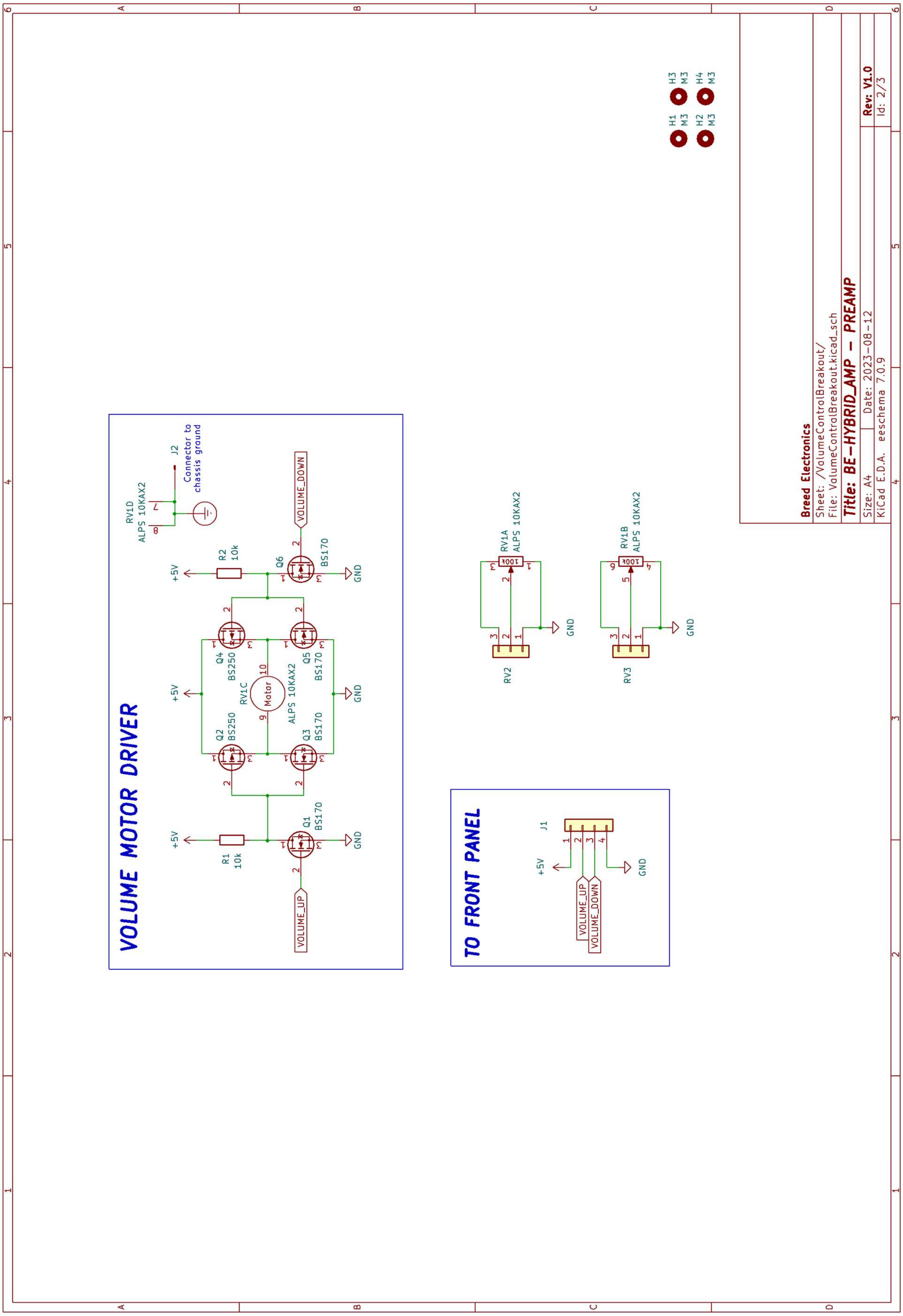


Figure 13 - Volume motor control

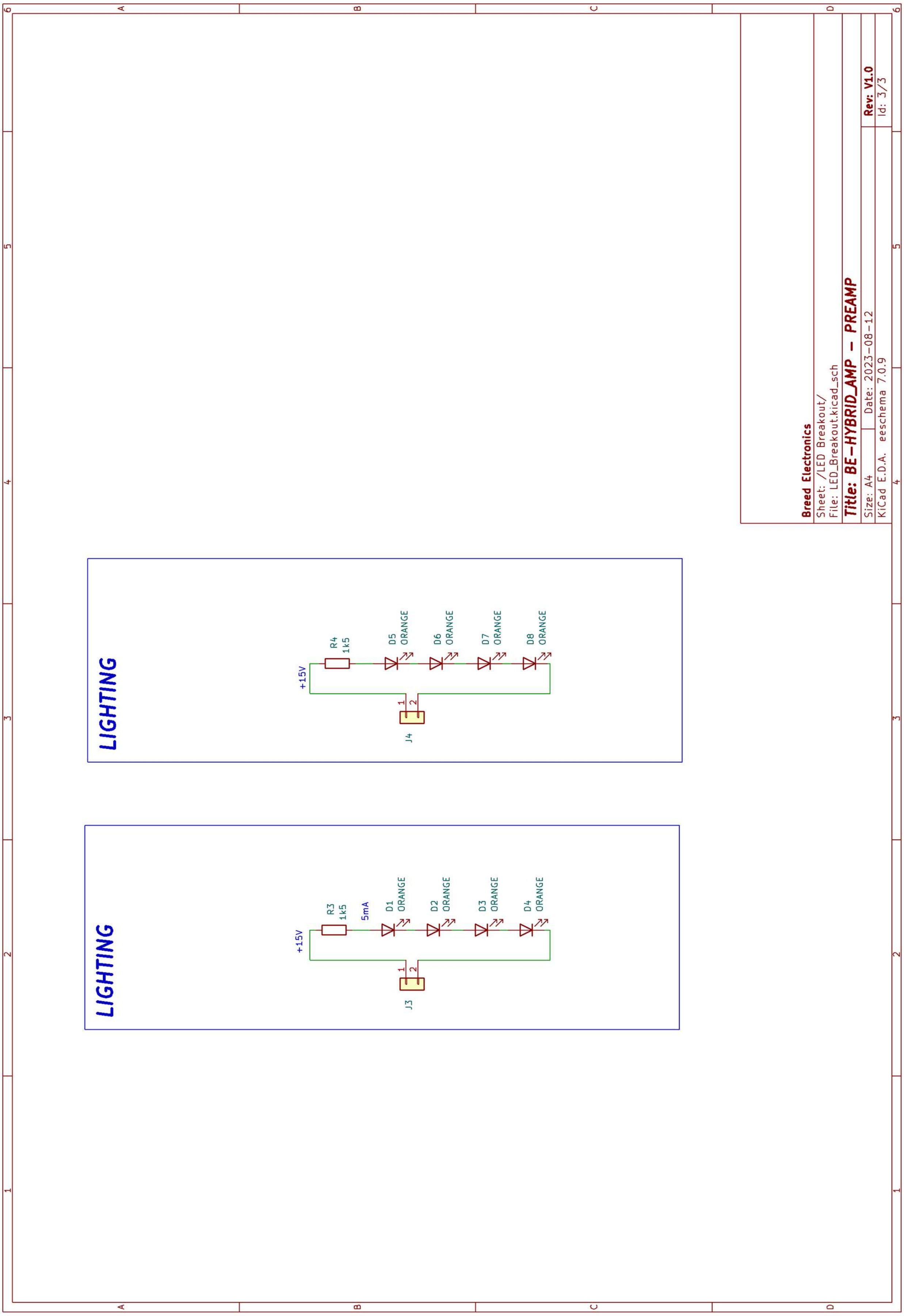


Figure 14 - Tube illumination

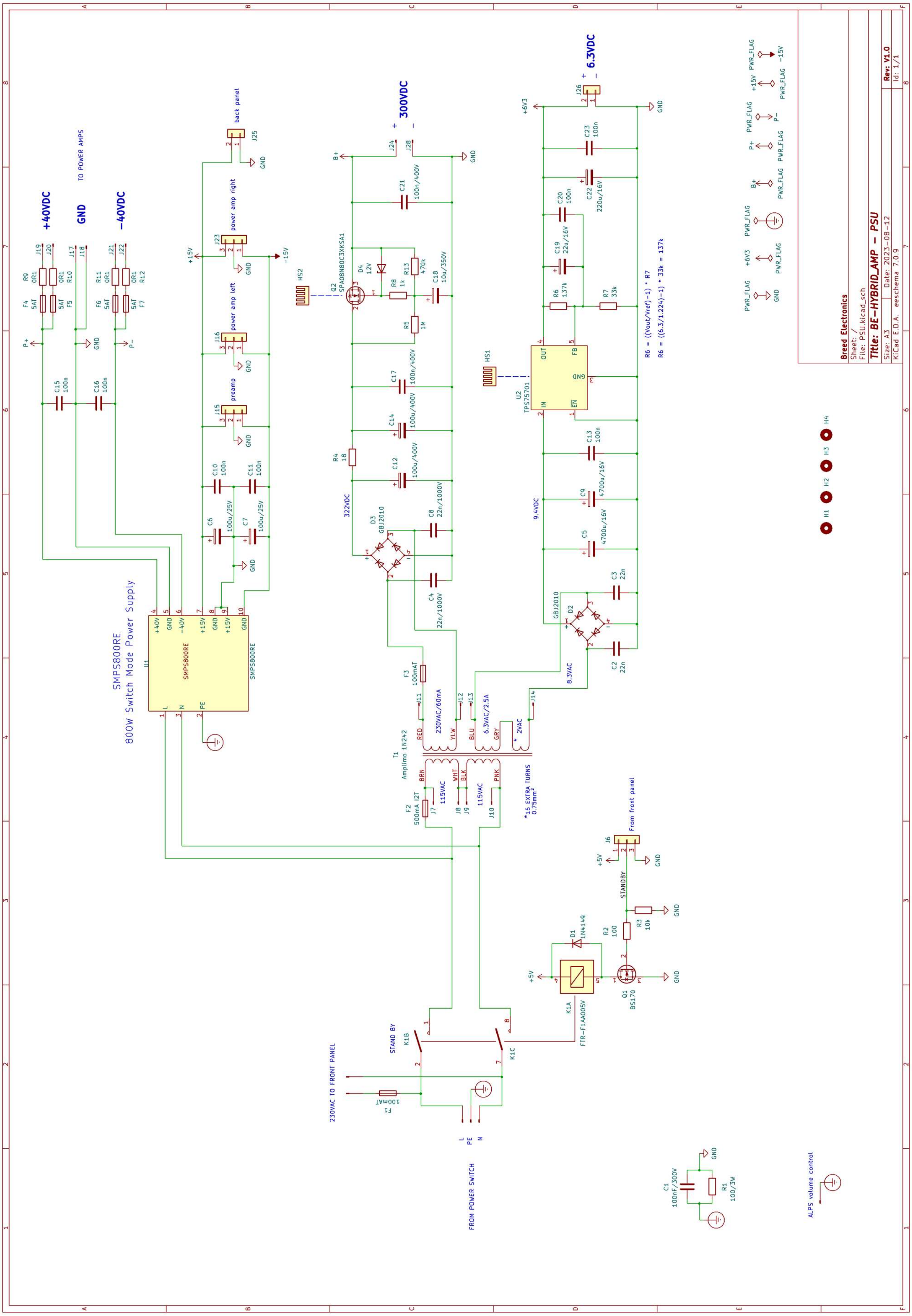


Figure 15 - Power supply

Switched-mode Power Supply

This amplifier uses a Switched Mode Power Supply instead of a linear power supply with transformer to power the mosfet amplifier. A Connex SMPS800RE is used to do the job. It's capable of delivering a continuous power of 800 W and is used to create the +/- 40 V and the +/- 15 V rails out of 230 or 120 Vac mains voltage and is specially designed for audio amplifiers. It has built-in under-voltage, over-voltage, over-current and over-temperature protection. When switched on the inrush current is restricted by an NTC which is bypassed by a relay after a 1 second delay.

Figure 16 - Connex Electronics SMPS800RE Switched-mode Power Supply

High efficiency (95.2 %) 800 W continuous power, 1000 W peak switched-mode power supply, +/- 40 V, +/- 15 V

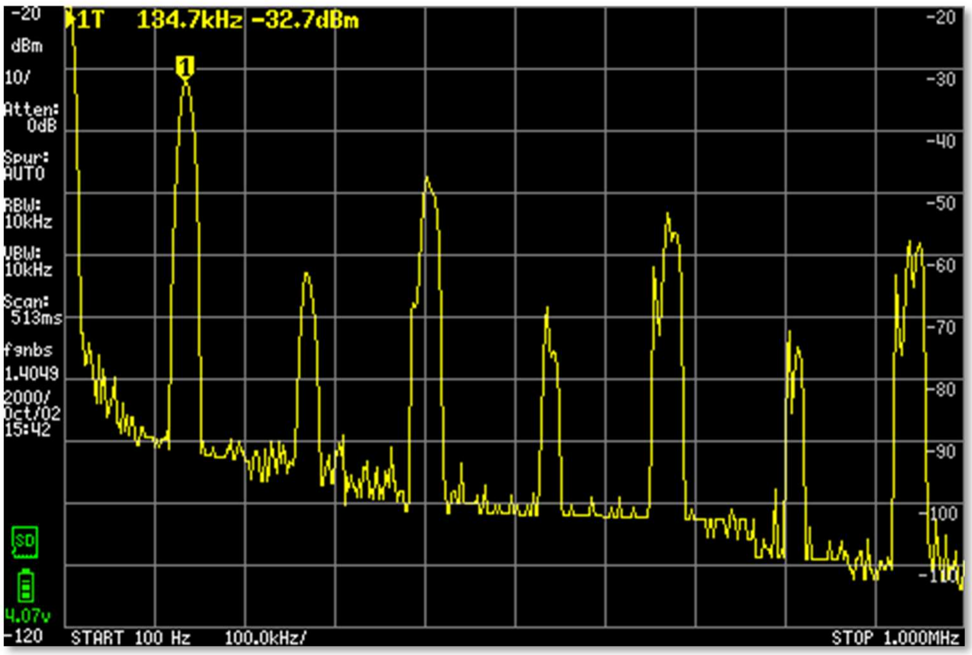


Figure 17 - Switching frequency measurement

The switching frequency of the power supply is measured with a tinySA spectrum analyzer and a near-field probe. The frequency turns out to be 134.7 kHz, which is well above the audio spectrum.

Measurement results

Spectrum 1kHz Tone - 8 Ohm / 1W – High Bias

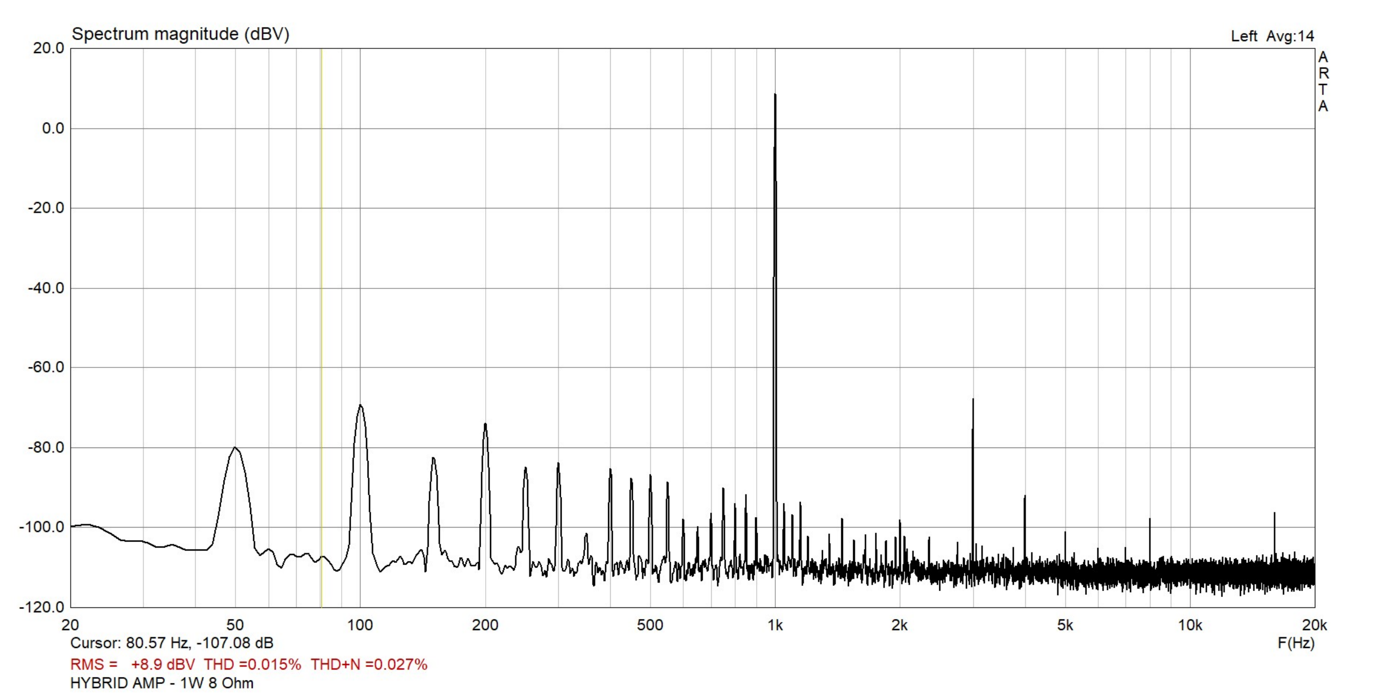


Figure 18 - Spectrum 1kHz Tone - 8 Ohm / 1W – High Bias

Spectrum 1kHz Tone - 8 Ohm / 1W – Low Bias

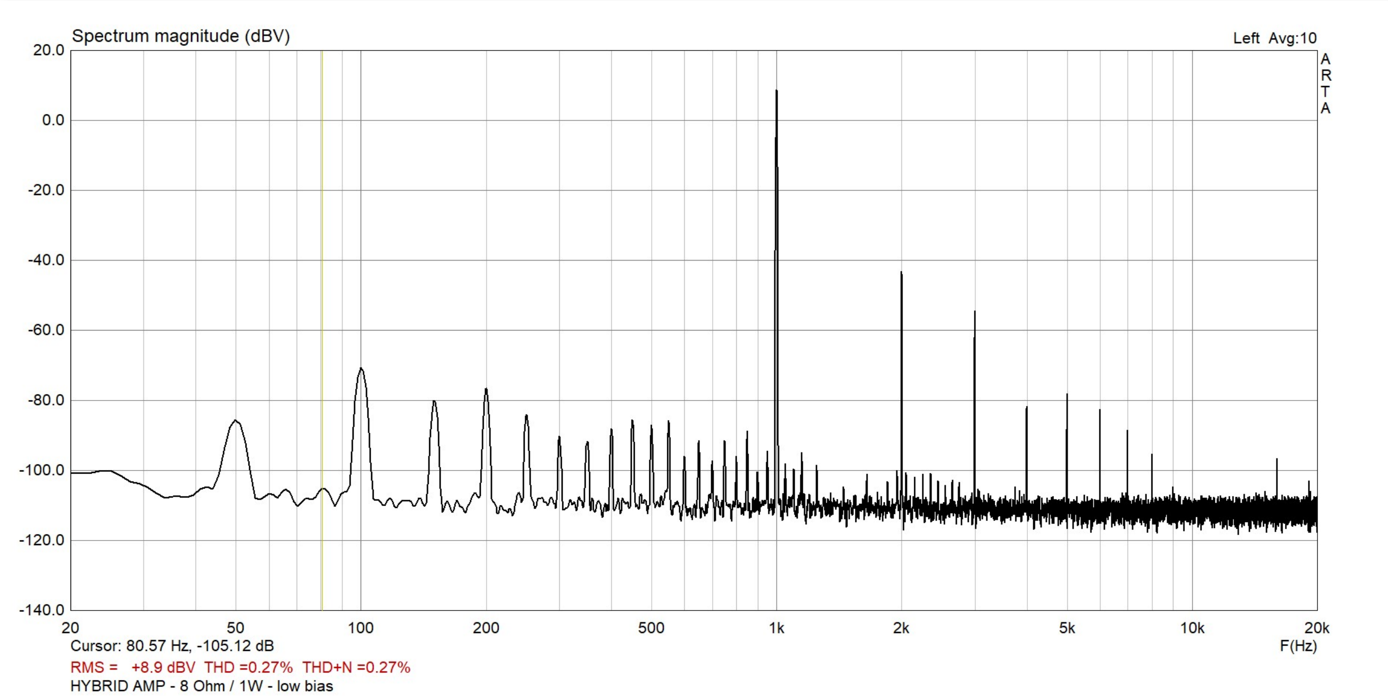


Figure 19 - Spectrum 1kHz Tone - 8 Ohm / 1W – Low Bias

Noise floor – input shorted

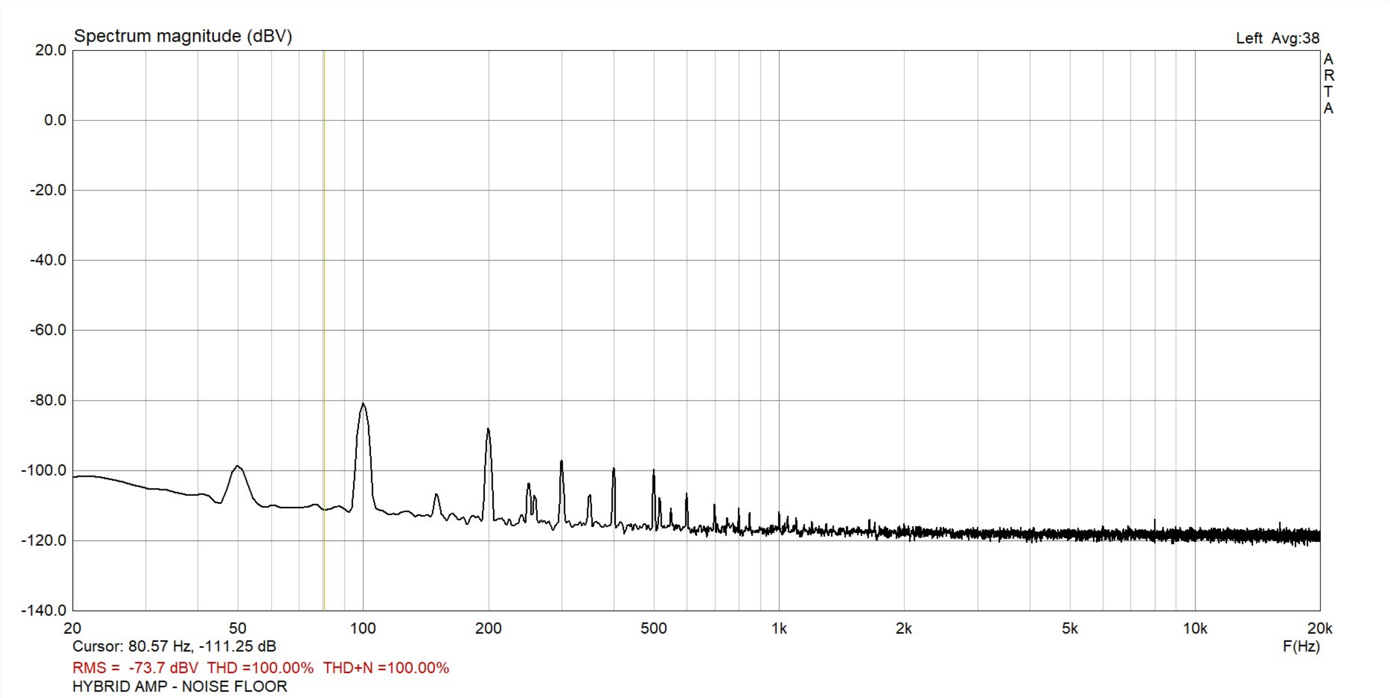


Figure 20 - Noise floor – input shorted

Bandwidth

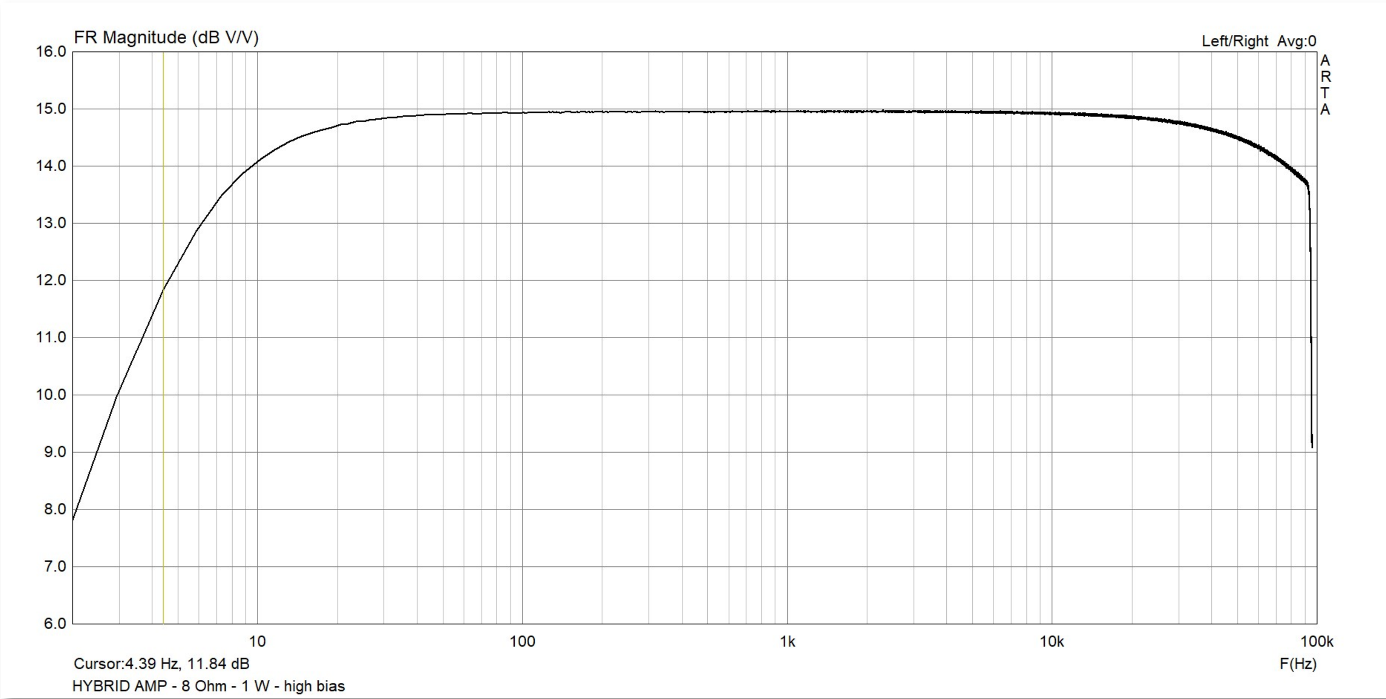


Figure 21 – Bandwidth ARTA

Bandwidth measurement with ARTA-2 and MOTU M4 soundcard. The soundcard does not have a high enough sample rate to measure the -3dB point at the high frequencies.

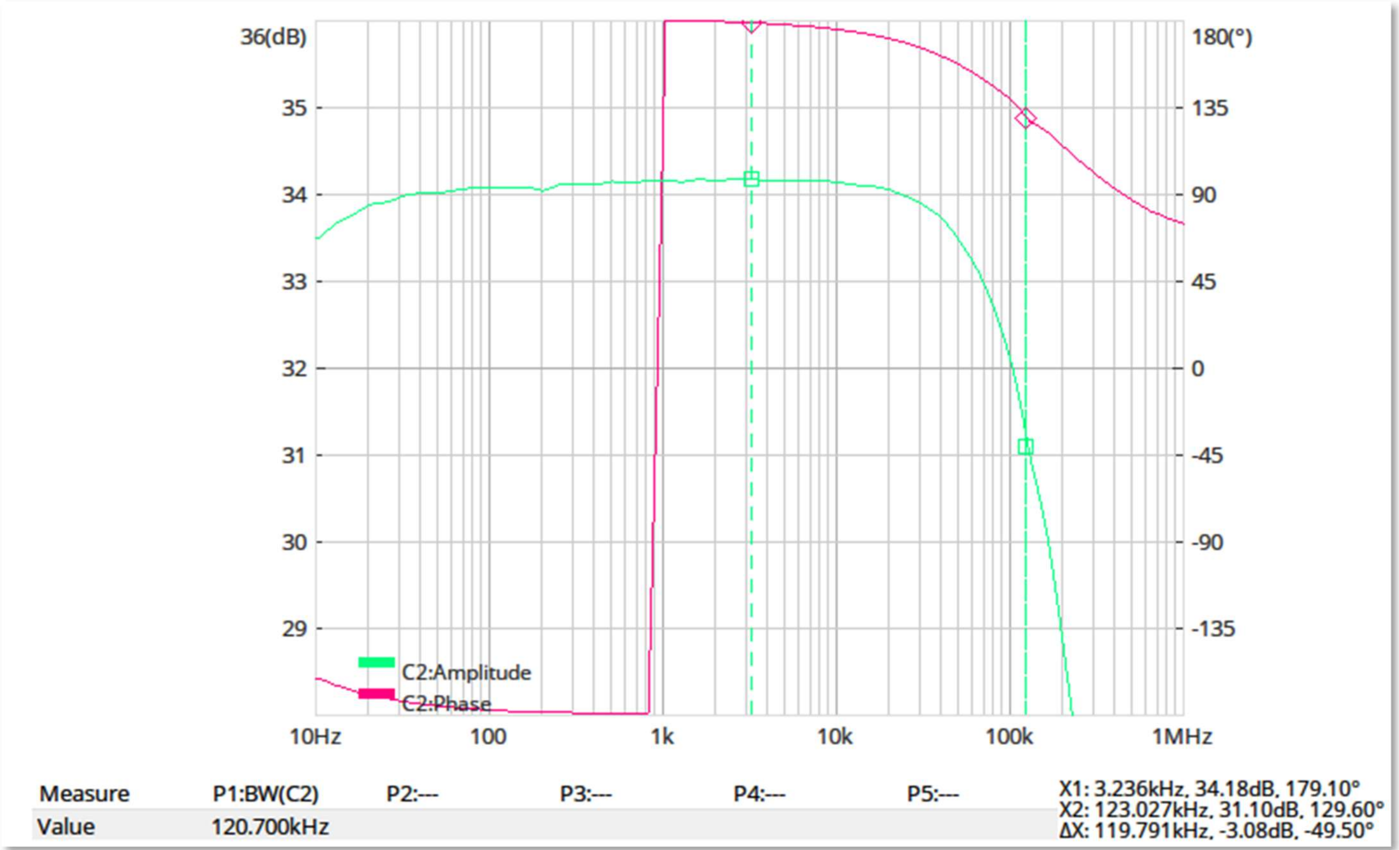


Figure 22 - Bandwidth scope

Automated bandwidth measurement made with a SIGLENT SDS5034X oscilloscope and SIGLENT SDG 1032X signal generator. This measurement cannot be done lower than 10Hz. Amplification factor is 50 (34 dB).

Distortion vs. Frequency

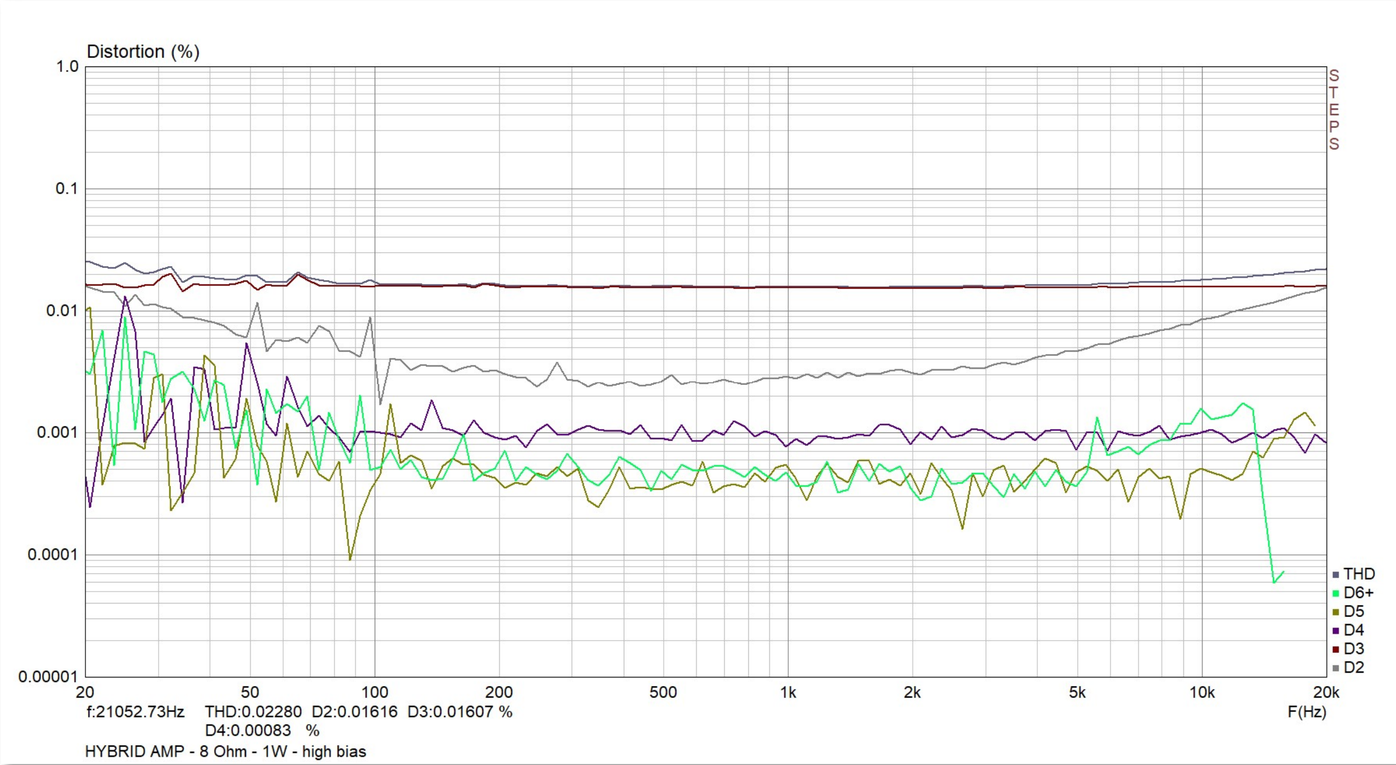


Figure 23 - Distortion vs. Frequency

Distortion vs. Output amplitude

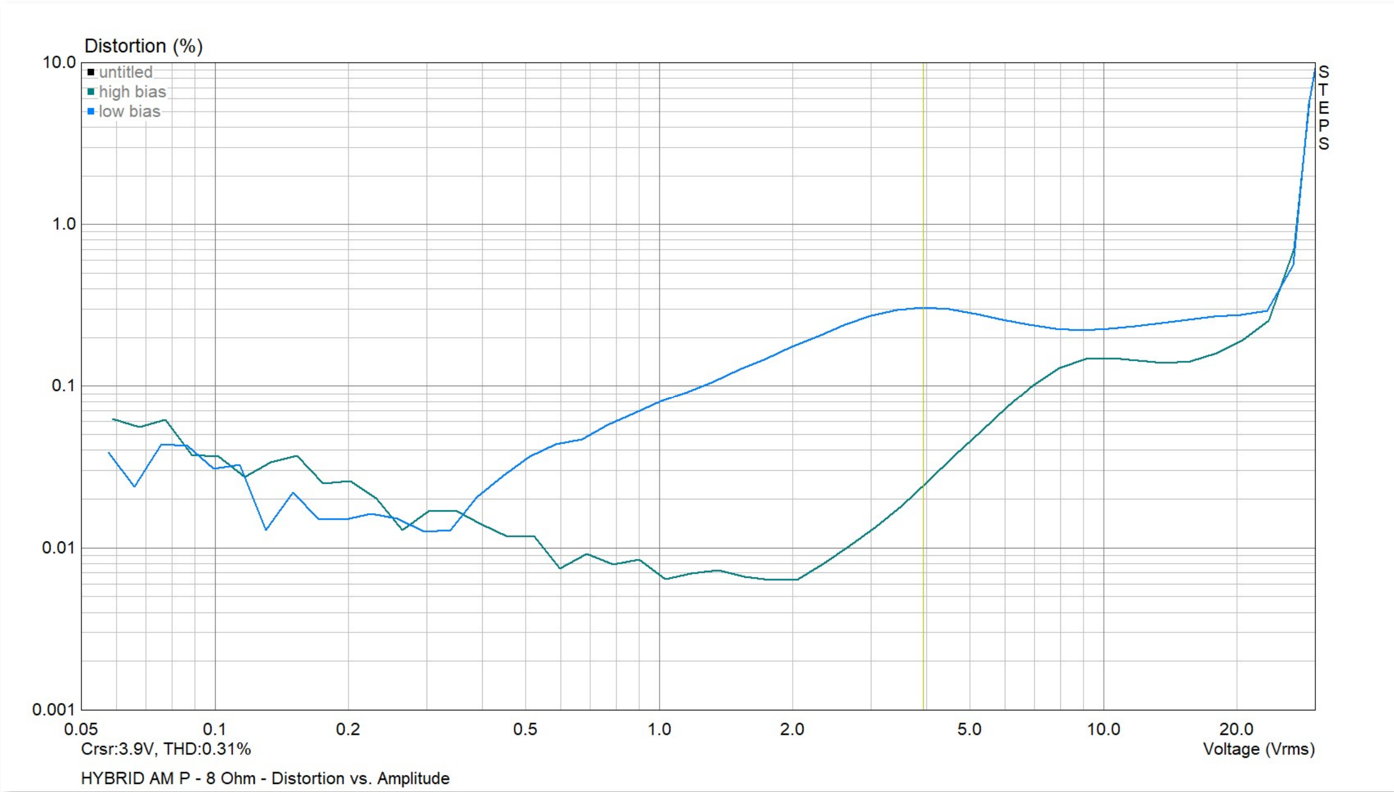


Figure 24 - Distortion vs. Output amplitude

Blue: Low-bias Green: High-bias

Impedance – low bias

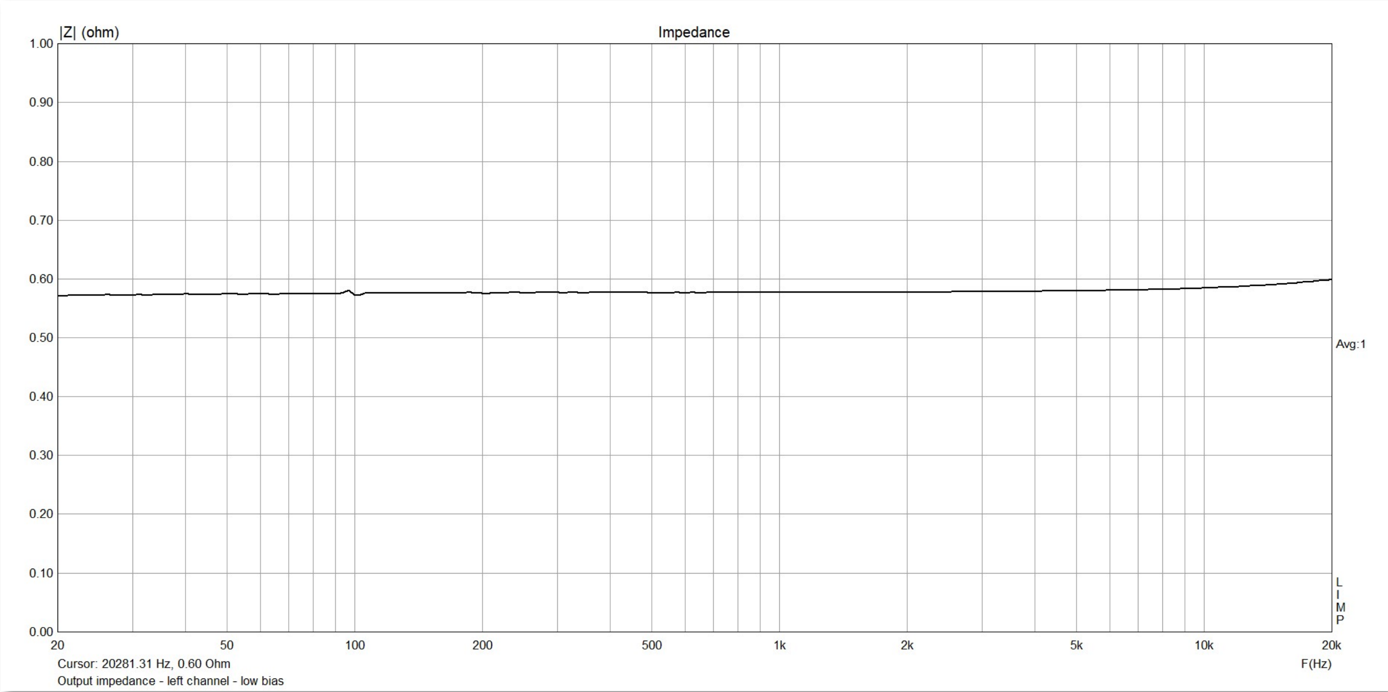


Figure 25 - Impedance – low bias

Impedance – high bias

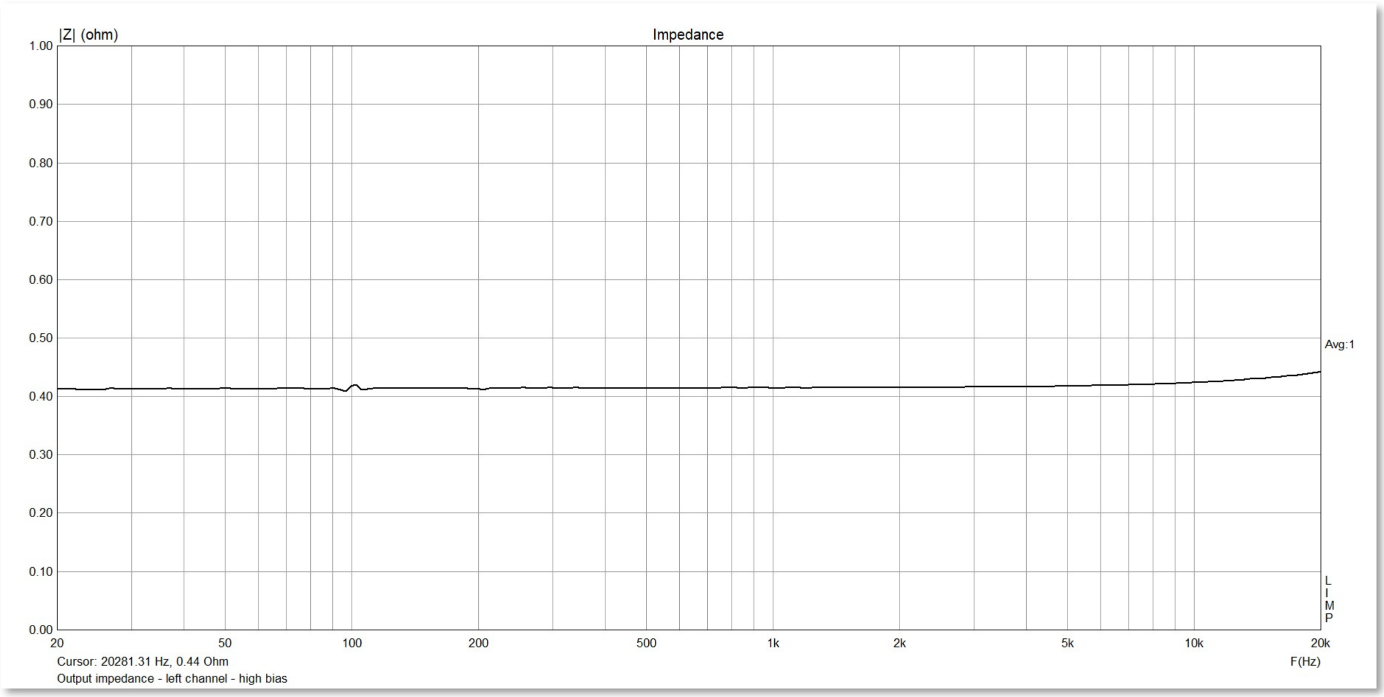


Figure 26 - Impedance – high bias

Tone control – controls at center position

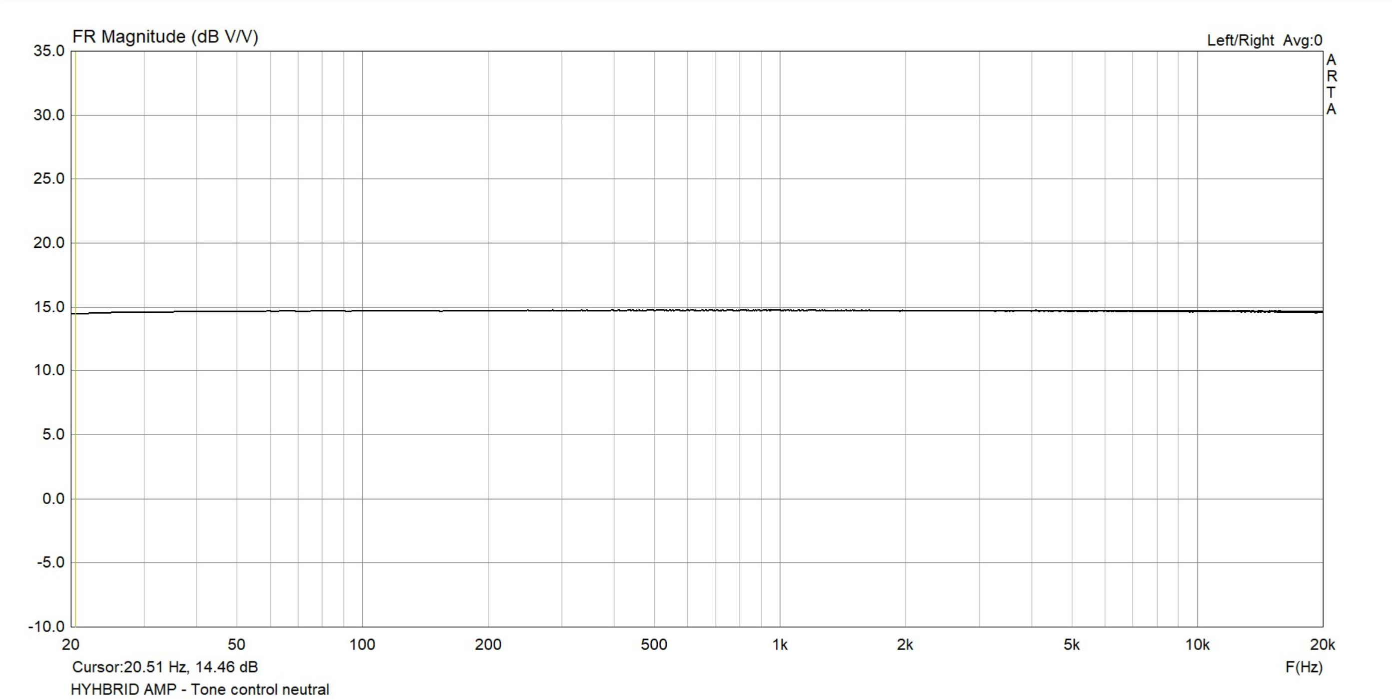


Figure 27 - Tone control – controls at center position

Tone control – range measurement

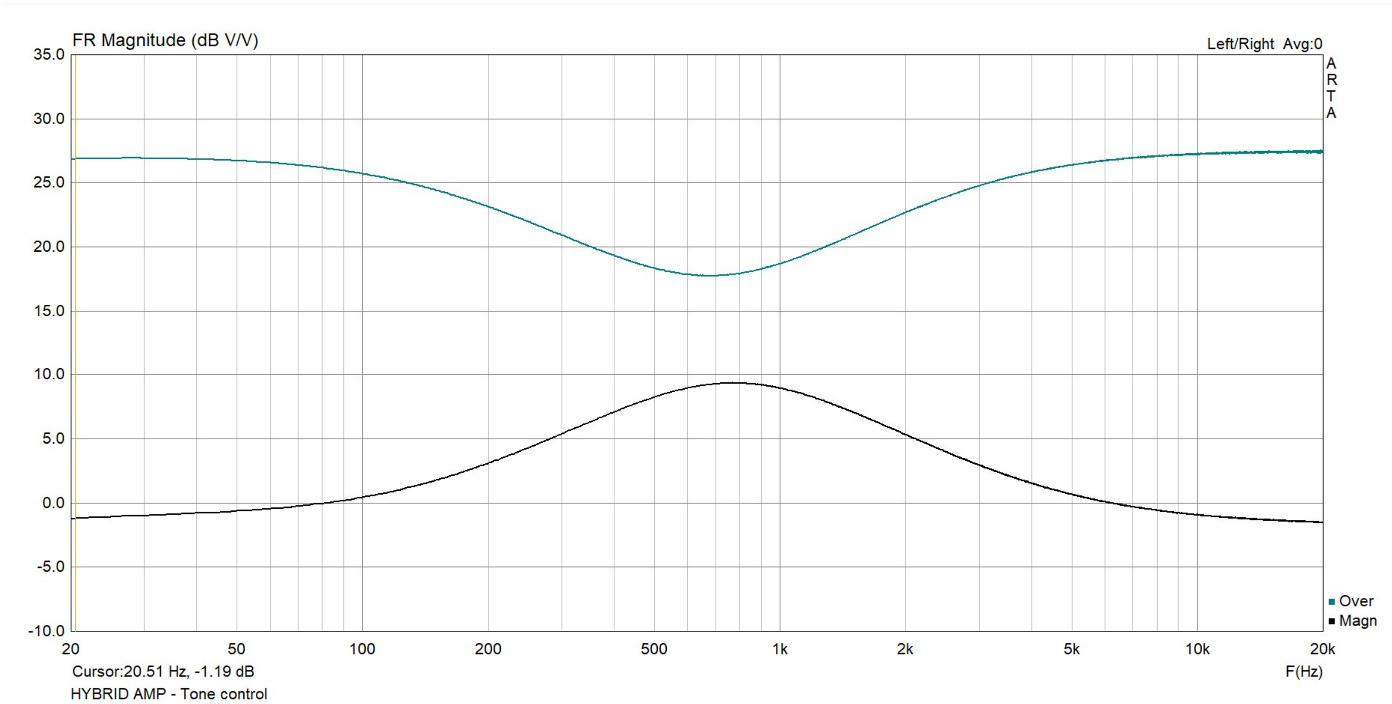


Figure 28 - Tone control – range measurement

Burst decay

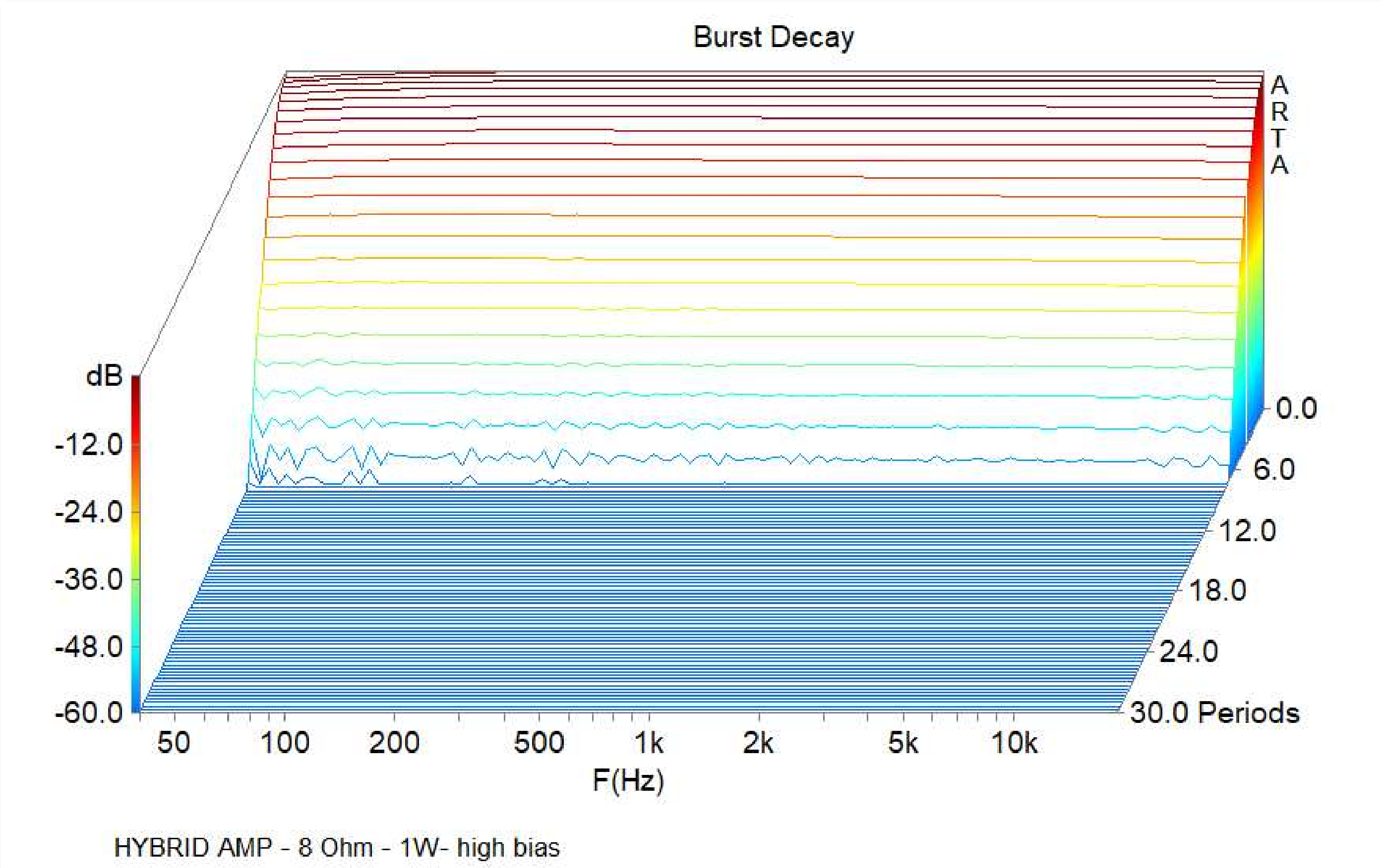


Figure 29 - Burst decay

3D Renders

Front panel pcb with preamp, microcontroller, tone control and vu meters

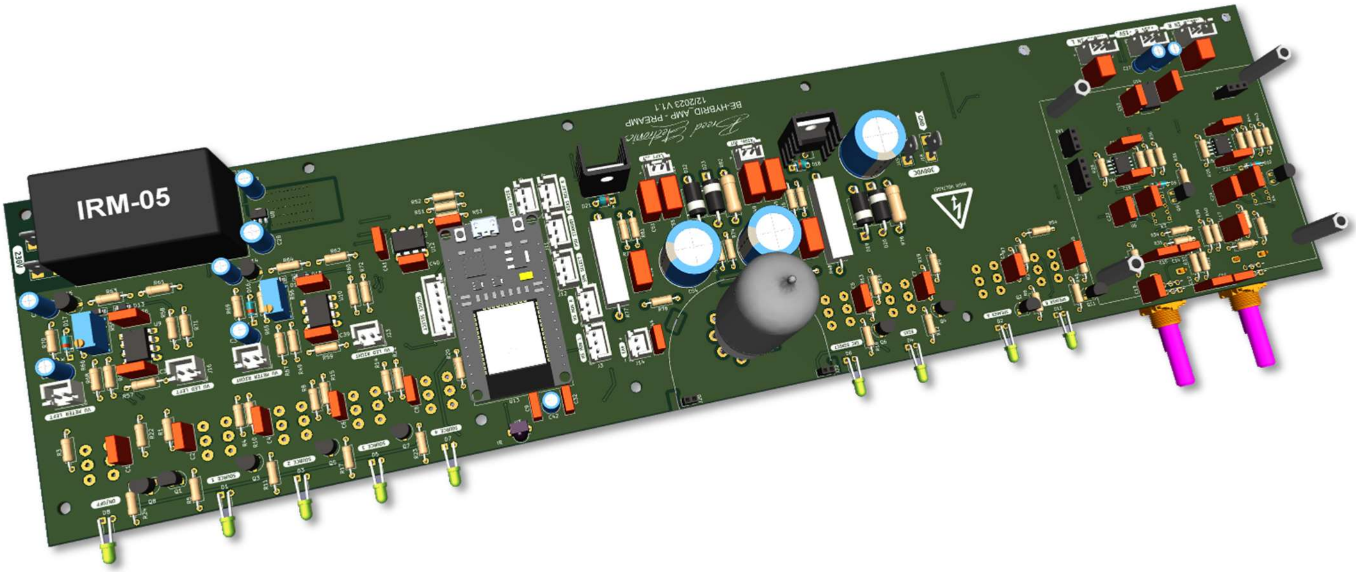


Figure 30 - Front panel pcb

Power amplifier – one single channel

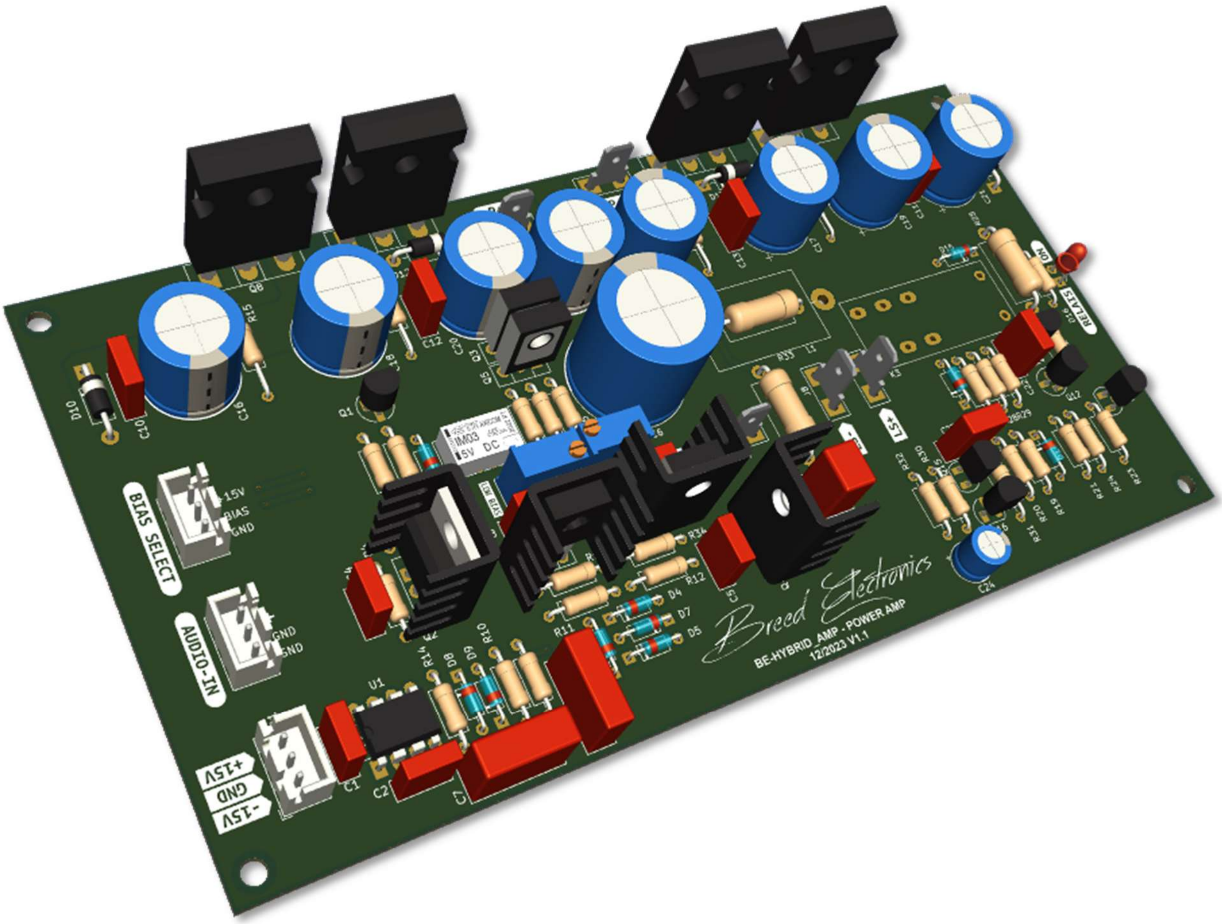


Figure 31 - Power amplifier pcb

Back panel – input and output relays

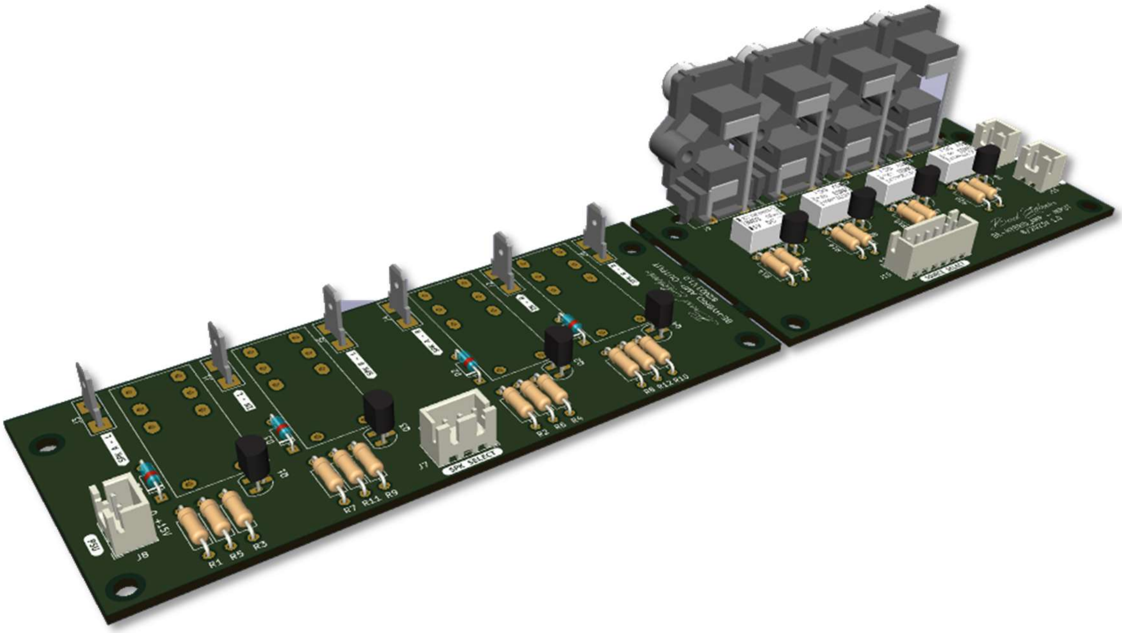


Figure 32 - Back panel

Volume control breakout pcb

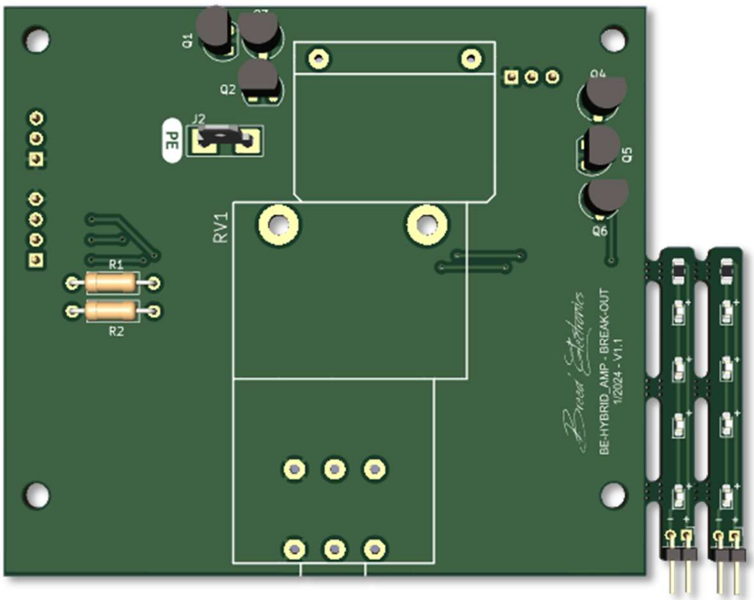


Figure 33 - Volume control and led breakout

The little pcbs at the right side can be taken off and contain orange LEDs used to illuminate the tube from the front.

300 Vdc and 6.3 Vdc power supply

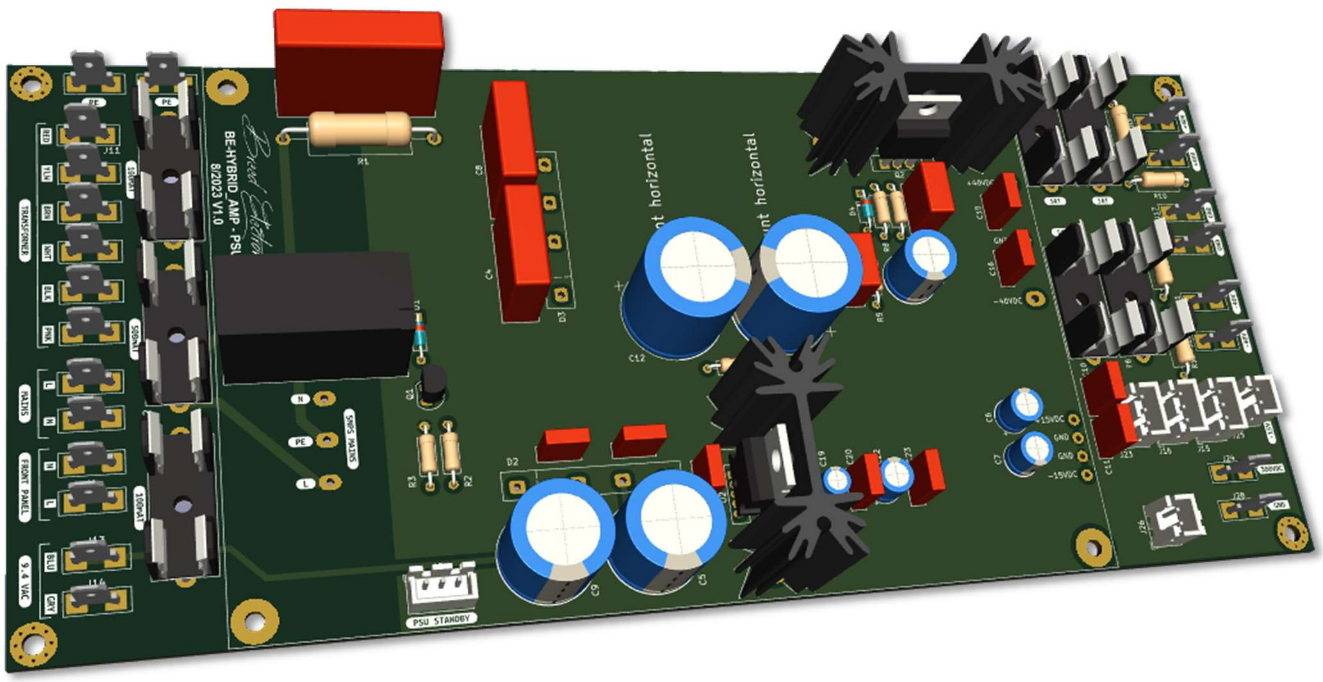


Figure 34 - Power supply pcb

Layout of the PCBs in the chassis

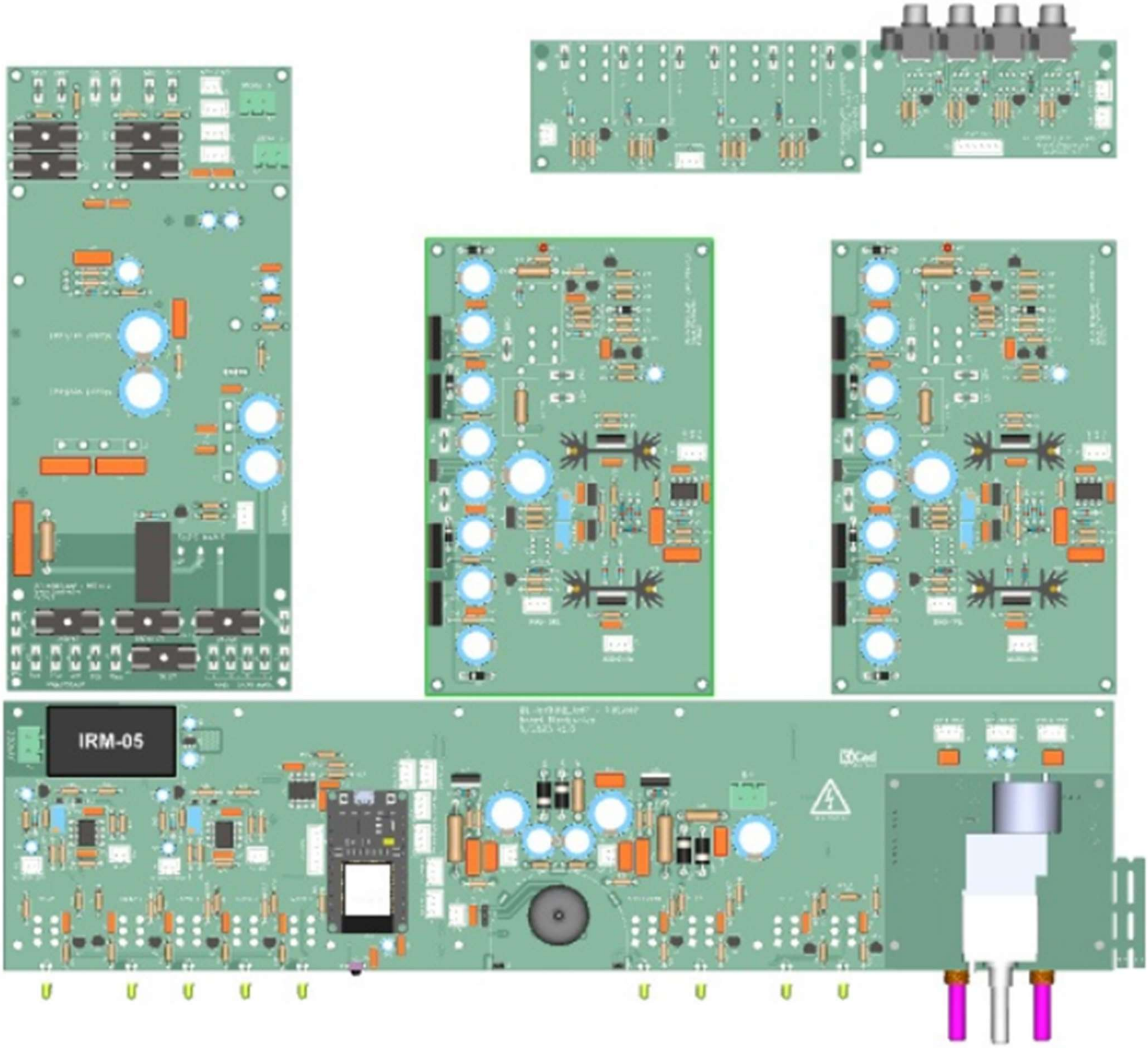


Figure 35 - Pcb layout in cabinet

LTSpice simulations

Simulation tools are handy to quickly check your calculations and the design. Changes are easily done and verified. A lot of time has been spent on simulating several parts of the amplifier before building it. Below are some examples of the simulations done for this project with the use of LTSpice.

Models of the Exicon ECX10N20 and ECX10P20 mosfets are used in the simulations. The model used for the ECC88 is of the actual tube used in the amplifier. The measurements to create the characteristics have been made using a uTracer V6 and the ExtractModel tool.

Amplifier simulation

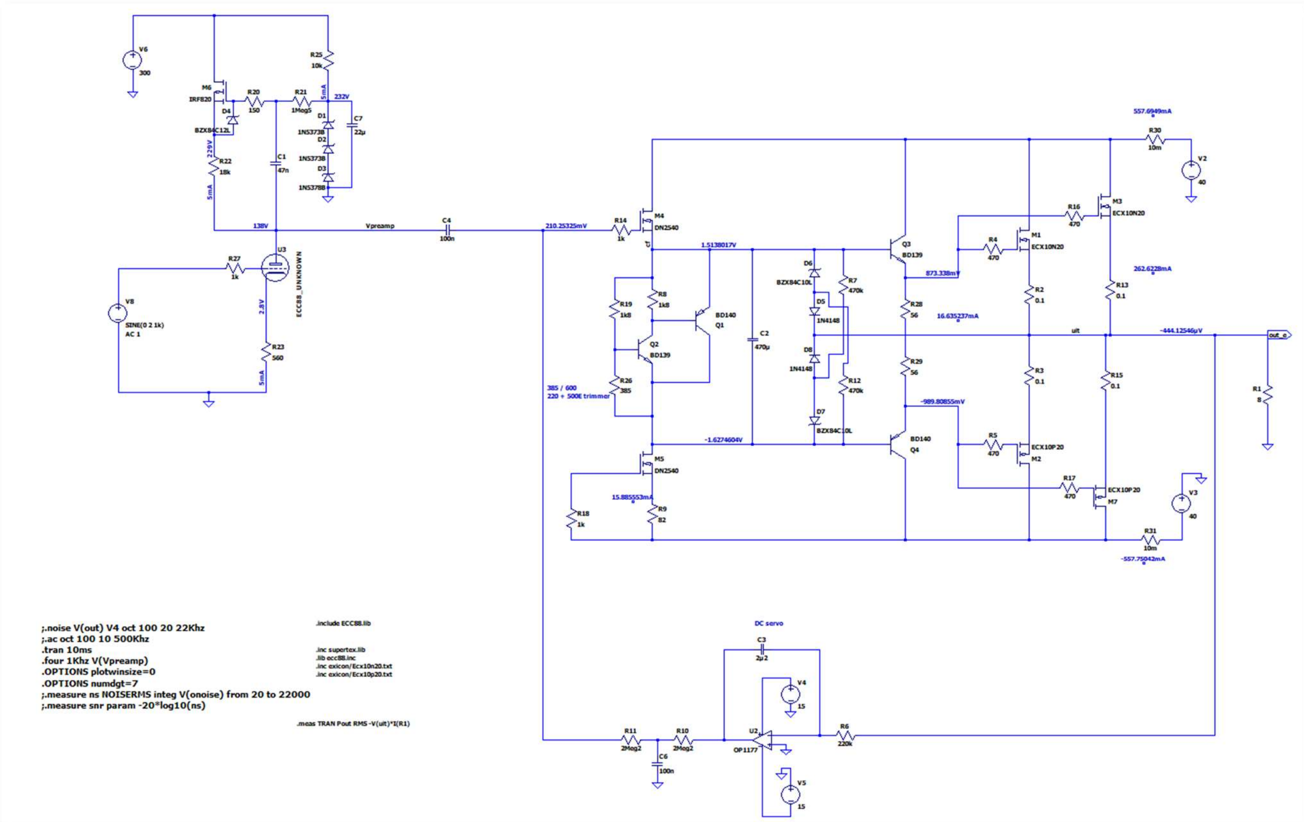


Figure 36 - Simulation schematics

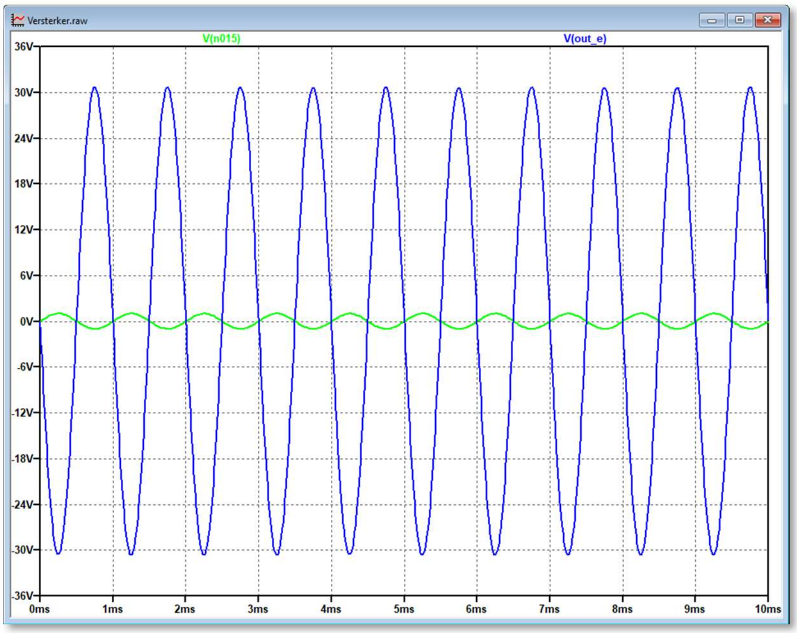


Figure 37 - Amplifier simulation results

Tone control simulation

The tone control has been simulated with different wiper positions of the potentiometers.

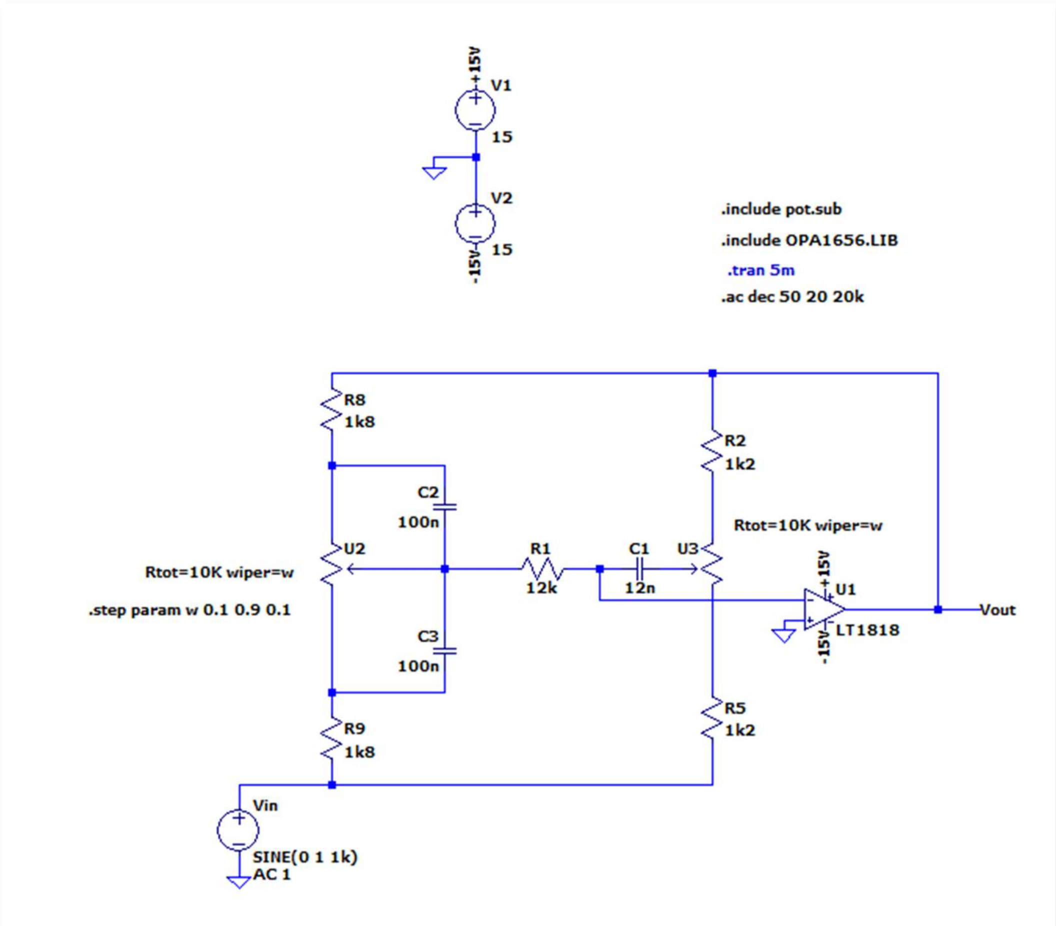


Figure 38 - Tone control simulation, schematics

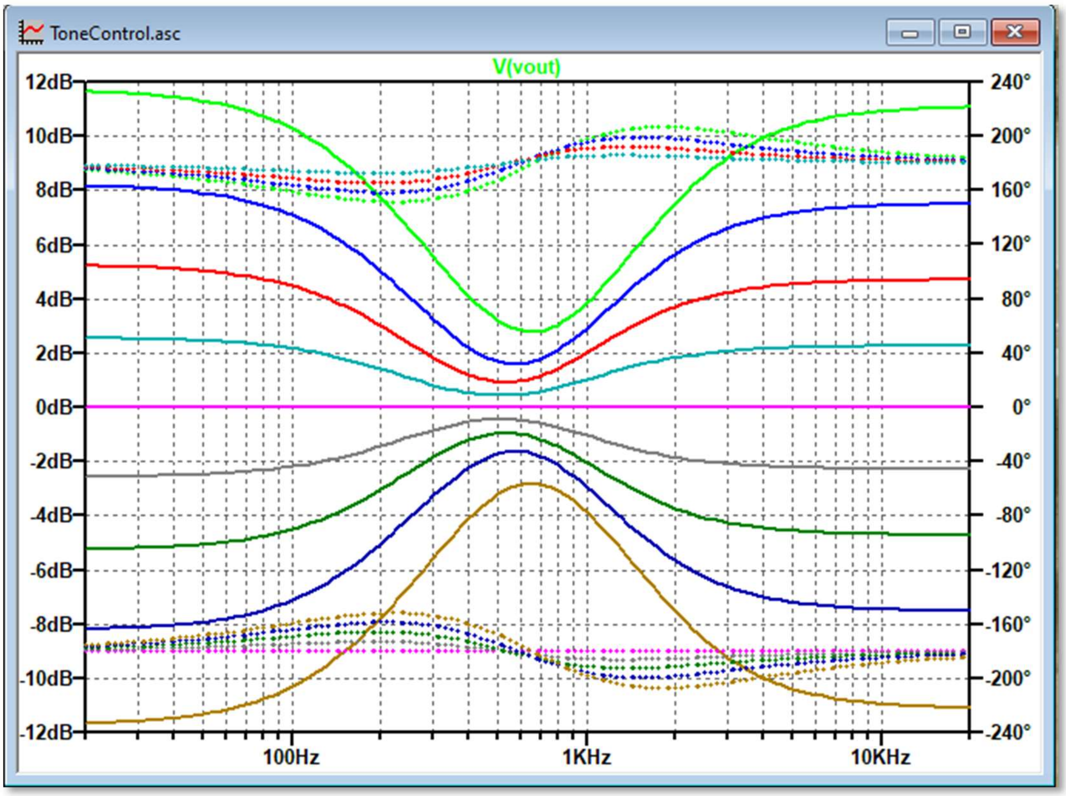


Figure 39 - Tone control simulation, results

Voltage limiter simulation

The microcontroller has an audio detection function. A voltage limiter is used to transform the audio signal to a signal between 0 and 2.2 V to prevent damage to the microcontroller input if the voltage becomes negative of higher than 3.3 V.

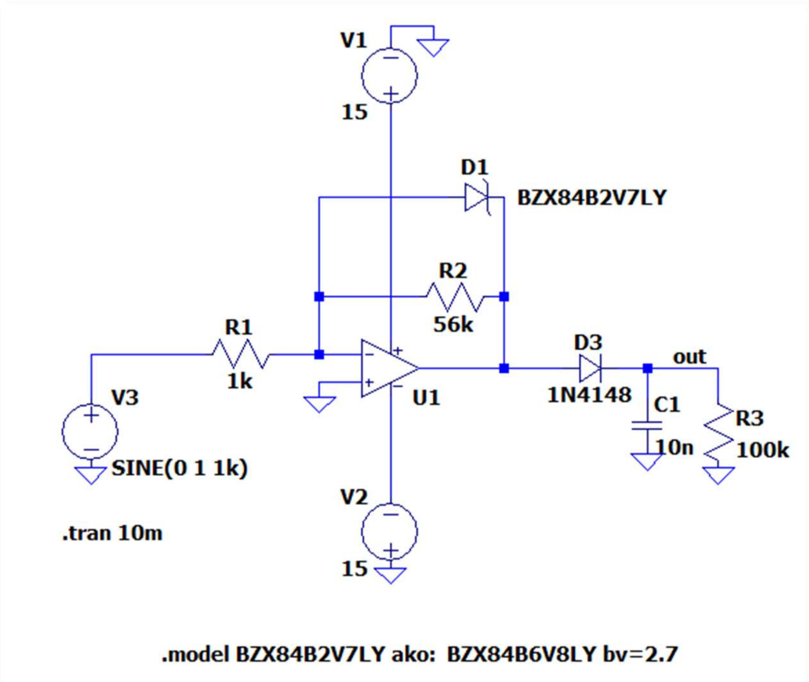


Figure 40 - Limiter simulation, schematics

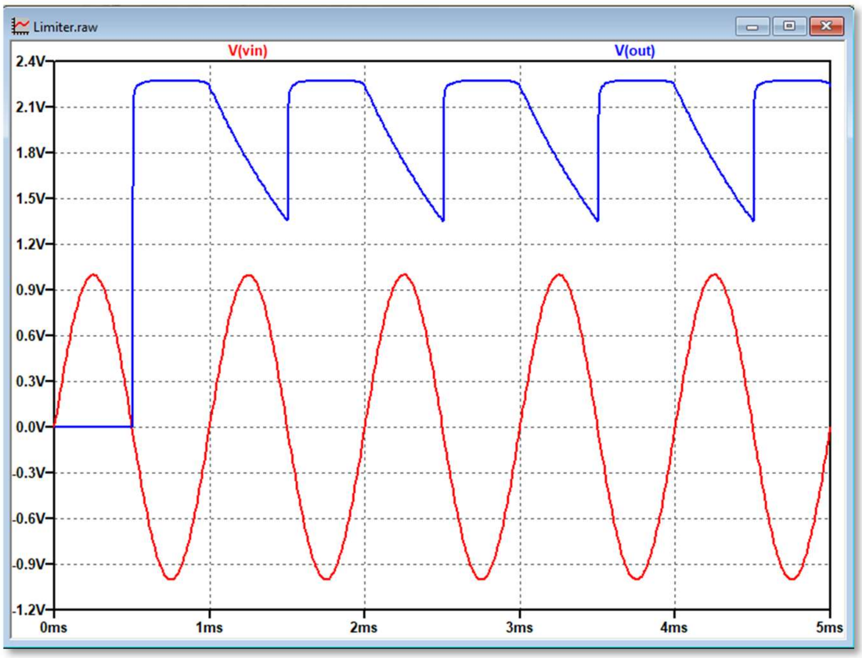


Figure 41 - Limiter simulation, results

Red is the input signal, blue is the output signal

Thermal management

For the calculation of the heatsink I have taken the power dissipation calculated by LTSpice when operating at 2/3 of the maximum output voltage and with 200 mA bias current (high-bias). The dissipation is 11 W per mosfet. When mounting 4 mosfets on one heatsink the total power to dissipate will be 44 W.

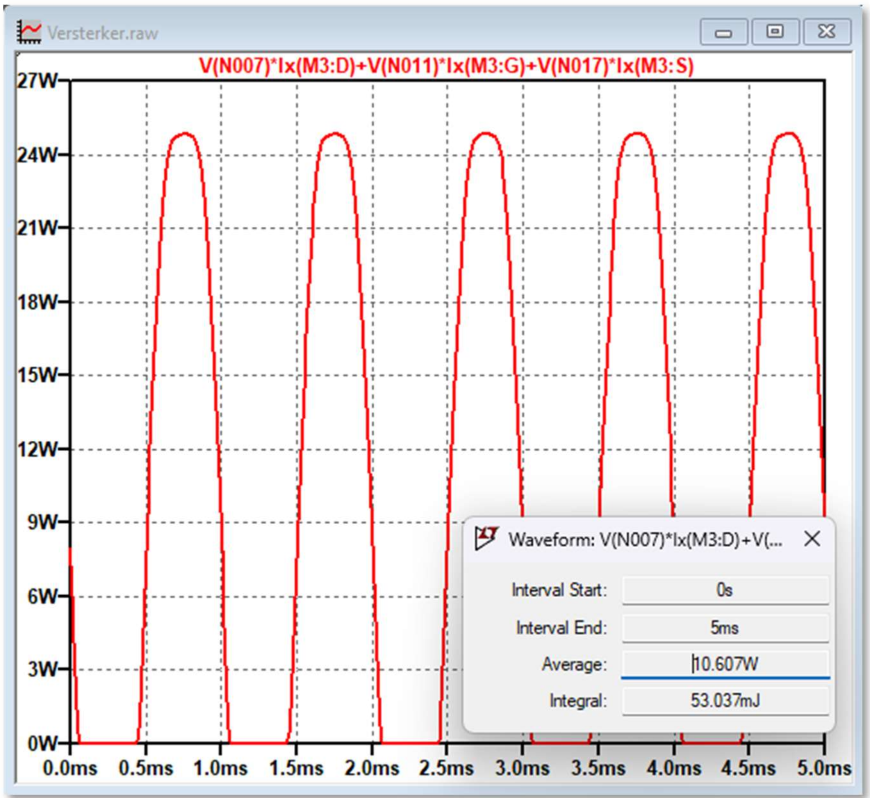


Figure 42 - Mosfet power dissipation

Below the calculation for the heatsink. I've taken an ambient temperature of 30 °C. The maximum junction temperature of the mosfet is 150 °C and the junction-to-case resistance is 1 °C/W according to the mosfet datasheet. The silicon isolation pad has a thermal resistance of 0.4 °C/W. After taking a spreading resistance of 30% into account it seems a heatsink with a thermal resistance of 0.88 °C/W is needed. I used a 0.9 °C/W heatsink in my design.

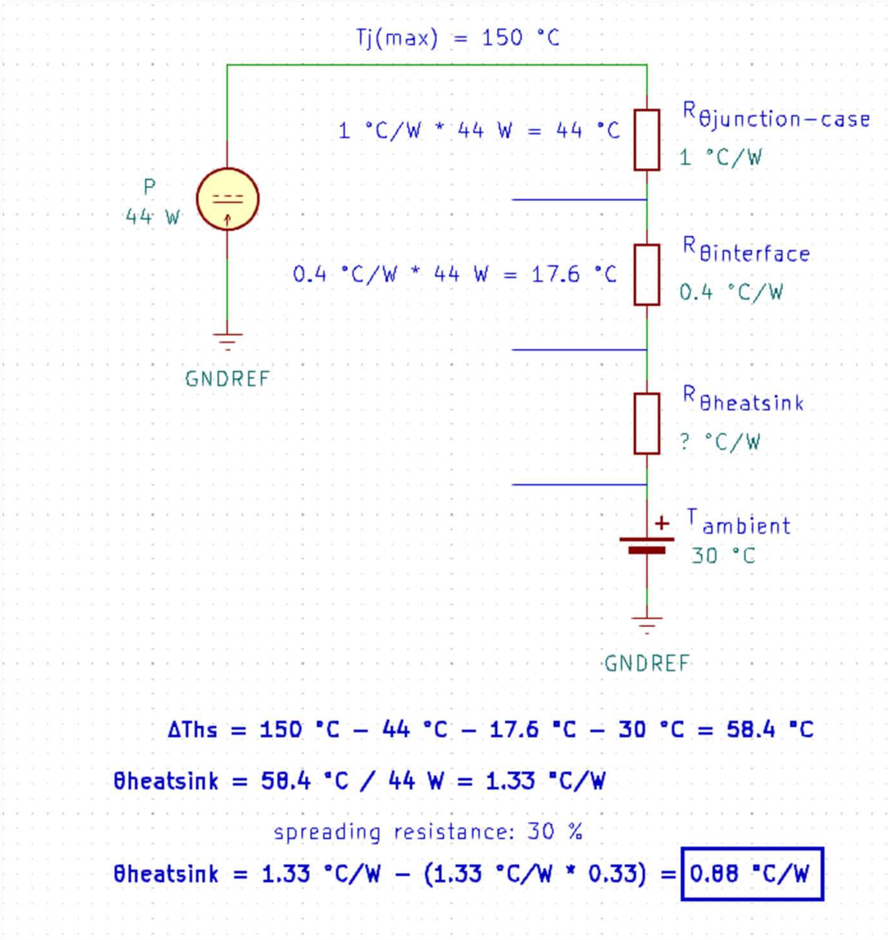


Figure 43 - Thermal calculation

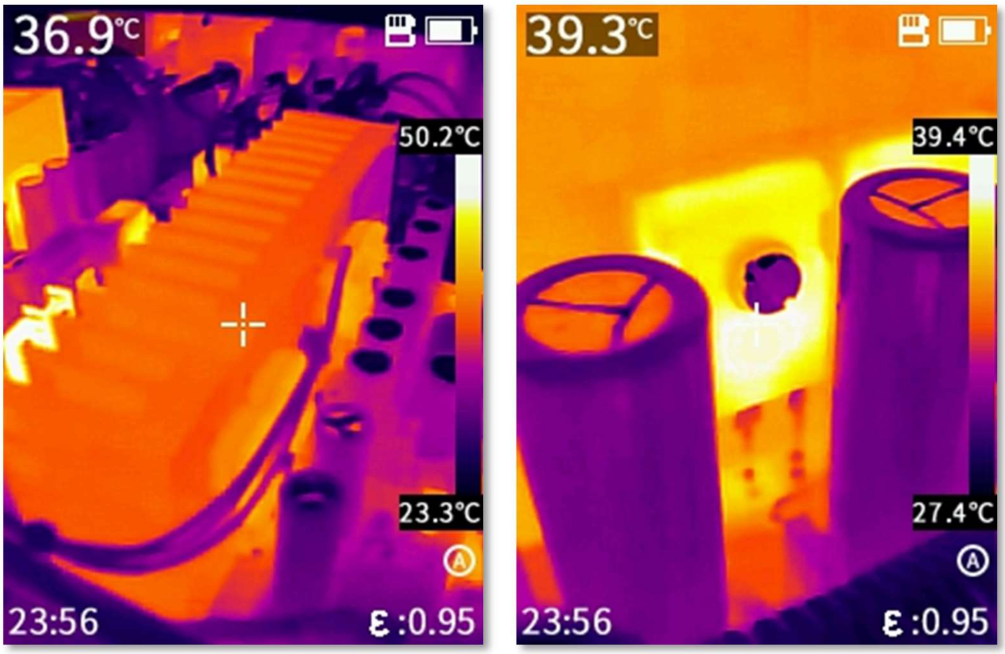
The heatsink temperature should become: (44 W * 0.9 °C/W) + 30 °C = 69.6 °C.

Temperature measurements

Heatsink temperature – High Bias, after 30 minutes

Thermal image of the heatsinks when the amplifier is operating in high-bias mode for 30 minutes. The heatsink temperature is 62 °C, the mosfet case temperature is 78 °C. At this time the current through each mosfet is about 200 mA.

Heatsink temperature – Low Bias, after 30 minutes



Thermal image of the heatsinks when the amplifier is operating in low-bias mode for 30 minutes. The heatsink temperature is 37 °C, the mosfet case temperature is 39 °C. At this time the current through each mosfet is about 30 mA.

Oscilloscope measurements

Figure 44 - Voltage levels just before clipping starts

Figure 45 - Measurement of the output voltage (yellow) with a square wave at the input (red)

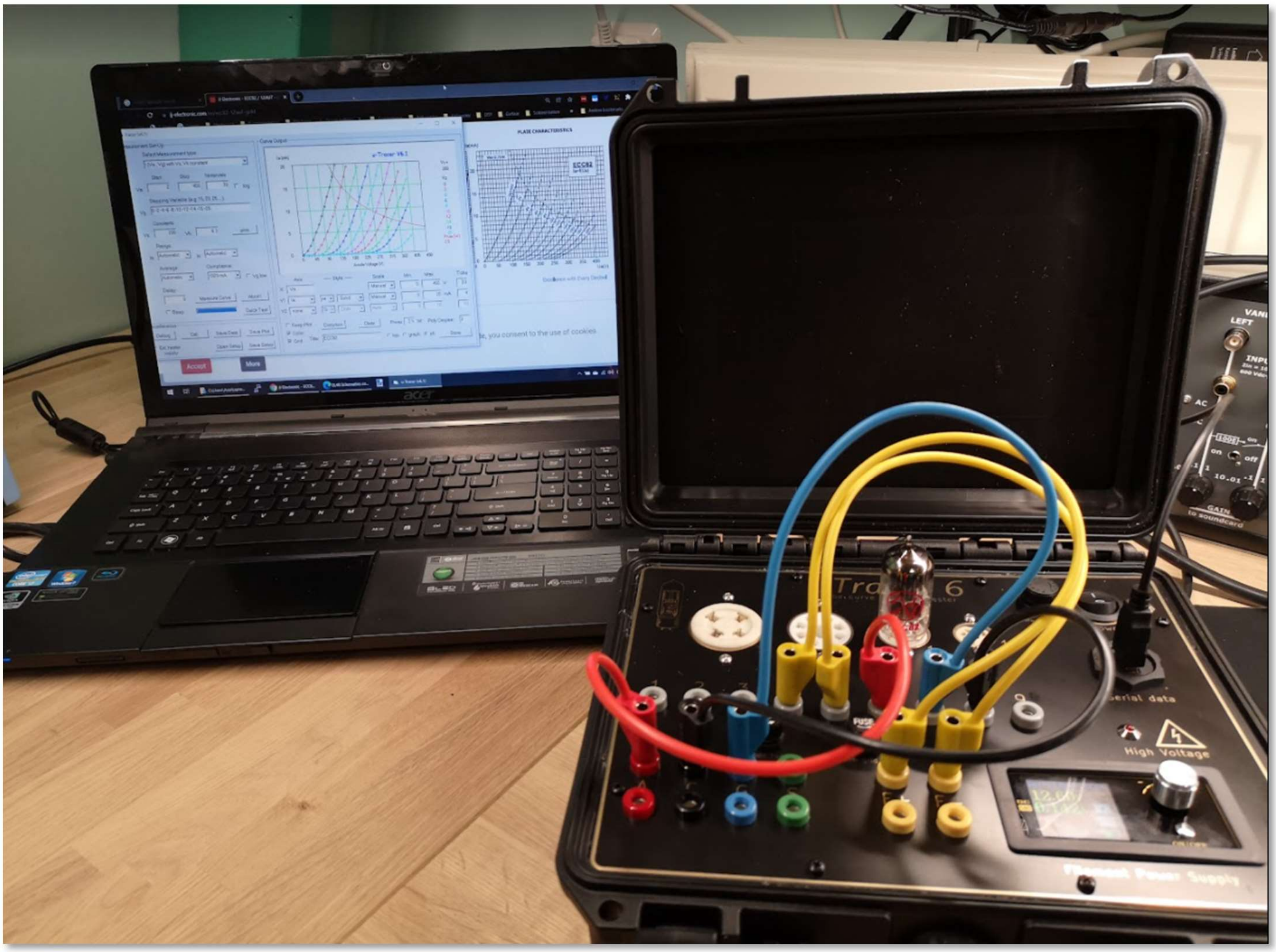


Figure 46 - uTracer connected to laptop

I've built a uTracer-6 for measuring tube characteristics and creating spice models of them. In this photo you can see the uTracer in the black case. It is connected to the laptop via USB. The laptop screen shows the measurements done by the device on the left in colour and the datasheet on the right in black and white.

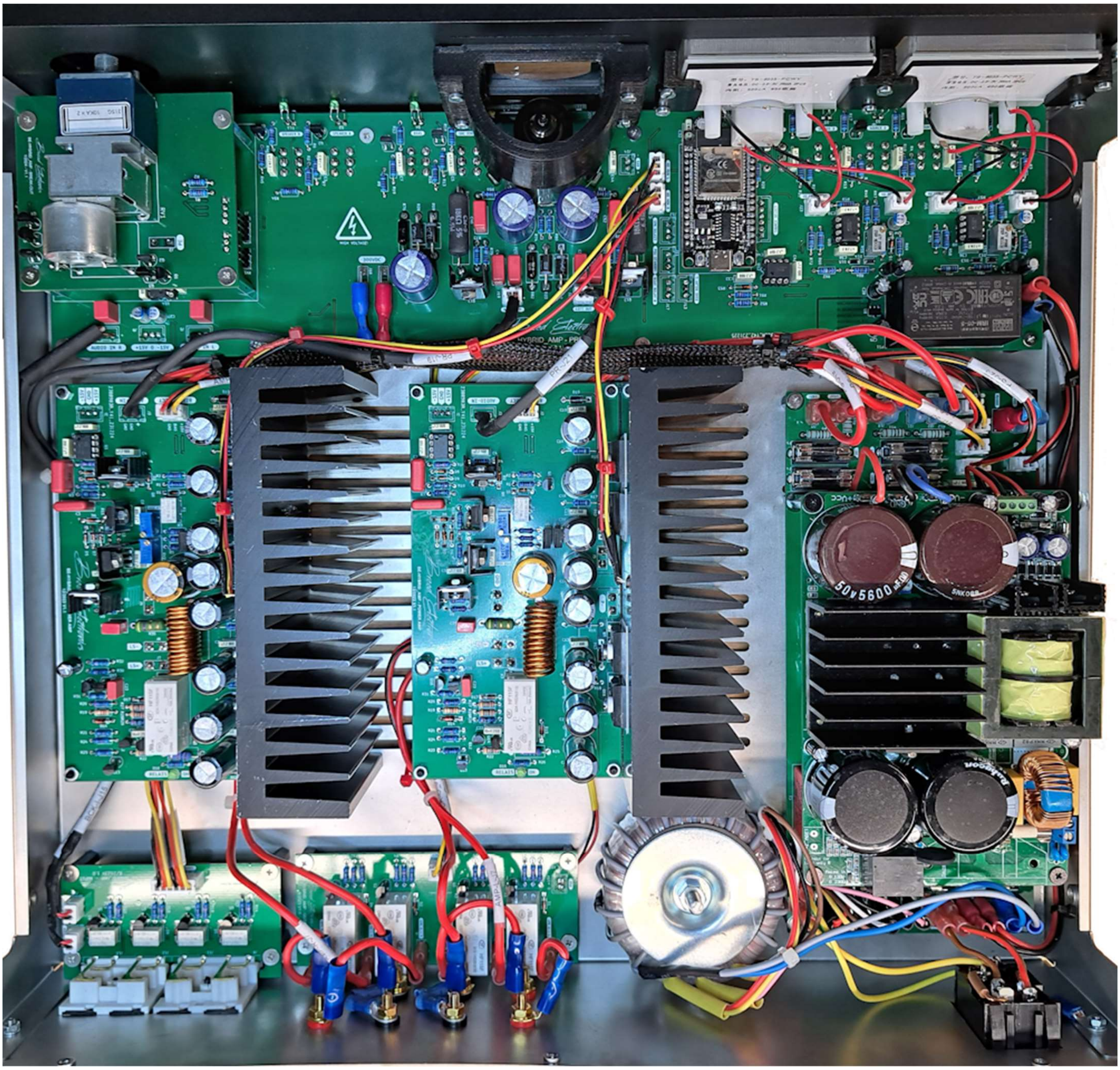


Figure 47 - The inside of the amplifier casing

Figure 48 - Remote control

Figure 49 - Backside of the amplifier

Figure 50 – Topside of the amplifier

References

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