Thermionic Valves and Guitar Amplification

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Abstract

The goal of the project was to build a functioning guitar valve amplifier. Guitar amplifiers powered by valves are still the most popular ones amongst musicians, therefore valve technology is not obsolete. This goal was achieved, the report includes documentation of the amplifier's construction process as well as analyses and detailed schematics of its circuit. To allow everyone, who is interested in electronics, electric guitar or both, to understand these, even though they might have no or little previous knowledge about valves, the paper provides a broad introduction into the world of valves, explaining how they work and how amplifier circuits can be built with them. Additionally, the report contains a variety of experiments and measurements conducted on valves to give better understanding how they work in a practical application.

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1. Introduction

Being heavier, bulkier and by far less efficient, it is not surprising that valves have been almost completely replaced by transistors. Nonetheless, their importance and value as a technological advancement in human history should not be underestimated. Before transistors were developed far enough to replace valves in the 1960's, people had to use the hot and power-hungry glass bulbs in order to amplify electrical signals. They were intensively used in audio amplification, radio communication and radar technology. However, nowadays, most people do not even know what valves are. This is not surprising at all. Only very few of the many valve models which were used during the 20th century are still used and produced today and the application for those valves are niche markets. The most important application these days for valves are amplifiers for electric guitars, as many musicians still prefer these old-fashioned amplifiers, which they praise for their better sound.

This paper will treat the basics in valve theory which are necessary to design amplifier circuits. It will also explain what the basic characteristics of a guitar amplifier are. The main goal of the project was to design and build a functioning valve amplifier for the electric guitar. The different sections of this amplifier were measured and analysed. Finally, some additional measurements on small signal valves were made to improve the understanding of how they work in a circuit.

2. Theory

2.1 Terminology Issues

Discussing valve circuits and theory can be difficult, since there is no naming convention everyone agrees on. The most prominent example for this are the different names for the valve itself. There is the American term vacuum tube, which is often abbreviated to tube, and the British term thermionic valve, which is abbreviated to valve. In this paper, the term valve is used. Another point is the differentiation between electric potential and voltage. With voltage being the difference in electric potential, it can only be expressed for a point relative to another point. In electronics, if the voltage of only one point is mentioned, the voltage between this point and a specific reference point is meant.

$$V_x = Electric\ potential\ of\ x - electric\ potential\ of\ reference\ point$$

$$V_y = Electric\ potential\ of\ y - electric\ potential\ of\ reference\ point$$

$$V_{xy} = V_x - V_y$$

This reference point is commonly the circuit's ground. However, in valve datasheets, when labelling the voltages of the electrodes the reference point is the valve's anode. Therefore, when discussing valve circuits in this paper, the standard reference point is ground, but if the voltage of a valve's electrode is mentioned, the reference point is not ground, but the anode of that specific valve.

Lastly, when referring to the size of a component like a resistor or capacitor, it is not the physical size but the value of the component which is meant.

2.2 Valve Theory

Fundamental Mode of Operation

Normal valves are used in every-day life to regulate the flow of liquids or gases. Thermionic valves serve the same purpose, yet it is not the flow of tap water or propane gas they control, but the flow of electrons. To accomplish this, valves take advantage of two physical phenomena: thermionic emission and electromagnetic force.

Thermionic emission, also called the Edison effect first discovered and described by Thomas Edison in 1883[1], occurs when a metal, semiconductor or oxide is heated above a certain temperature and emits electrons. The electrode of a valve which emits electrons is called the cathode. Those electrons remain close to cathode's surface. This cloud of electrons is called the space charge. Since the electrons are negatively charged and repel each other, there is an equilibrium at which the number electrons emitted is equal to the number of electrons repelled back to the cathode. Therefore, there is maximal number of electrons which can be in the space charge[2].

The temperature at which thermionic emission occurs is different for each material. In many valves, the cathode is made of nickel and coated with barium- and strontium-oxide. These oxides allow a low operating temperature of the cathode between 950K and 1050K. This makes it possible for the cathode to be indirectly heated by a dedicated heater filament. Other cathode materials require higher temperatures ranging from 1900K to 2600K and are directly heated. This means the heater filament is the cathode itself[3]. The oxide-coated indirectly heated cathode is by far more popular than the alternatives, since lower temperatures are required and indirect heating yields a great benefit which will become apparent later.

The requirement for active heating is also the reason why valves are less efficient than transistors in most applications. Transistors only produce heat as a by-product caused by the current flowing through them, which do valves as well, additionally to the active heating they require. The power consumption of the heater filament alone of a single ECC83 small signal triode, which can roughly be compared to a common small signal transistor, is 0.945 watts[4]. This value increases with bigger valves, like an EL34 needing 9.45 watts for the heater filament alone[5].

Electromagnetic force is the force which acts between two or more charged objects or particles. Like charges experience a repelling force whereas unlike charges experience an attracting force. Coulomb's law allows to calculate this force for two point charges q_1 and q_2 with a distance of r between them[6].

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

The formula is different if the two charges are not ideal point charges, but it always remains true that the force increases with the magnitude of the charges and decreases with increasing distance between them. This formula itself will not be very useful for our purposes, since the absolute charges of the components of the valve are unknown. The only known charge is the one of an electron, which is the negative value of the elementary charge q_e[6].

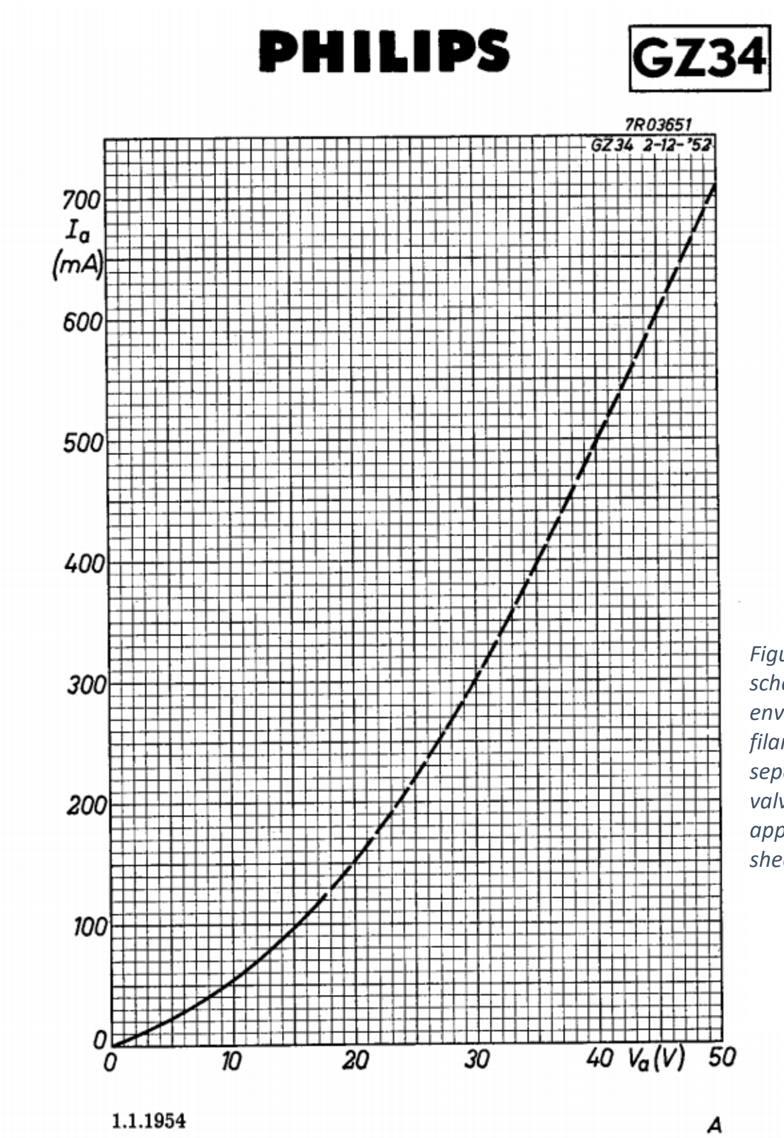
$$q_{e^-} = -1.602 \cdot 10^{-19} C$$

If an electron is between two fixed electrodes, it will, since it is charged negatively, be accelerated towards the electrode which is more positively charged. The resulting force on the electron is independent of the actual charge between the two points. The only important parameter is thus the difference in charge between the two electrodes. Between the two unequal charged electrodes exists an electric field. The field lines show the direction of this field, pointing from high to low electric potential. Therefore, in an electric field an electron is accelerated in opposite direction of the field lines.

Combining those two effects results in the fundamental mode of Operation of a valve. Electrons are emitted by thermionic emission from the heated cathode. The emitted electrons form a space charge. Some electrons leave the space charge accelerated towards another electrode, the anode, by electromagnetic force, while new electrons are emitted by the cathode emitted taking their place in the space charge. The magnitude of the electromagnetic force determines the number of electrons leaving the space charge per time and therefore the current through the valve. As the electrons move from the cathode to the anode the electric current flows per definition from anode to cathode. To reduce the amount of collisions between the accelerated electrons and gas molecules the glass envelope of the valve is evacuated. The pressure within the valve needs be reduced far enough that the mean free path of an electron is sufficiently higher than the distance between cathode and anode.

Valve Diode

The simplest type of valve is the diode, also called Fleming diode, invented by John Ambrose Fleming in*. It consists only of a cathode, an anode and the heater filament. In schematics, it is represented by the symbol seen in Figure 1. If the anode voltage V_a is positive, electrons from the space charge will be accelerated towards the anode and impact on it creating the anode current I_a. Figure 2 illustrates this process qualitatively. If V_a is not positive, no current can flow. The valve diode works therefore similarly to its successor: the silicon diode, as they both only let current pass in one direction. However, there is a significant difference. While a silicon diode has a certain breakthrough voltage, above which its resistance decreases very rapidly to a fraction of an ohm, the resistance of a valve diode is magnitudes higher and decreases less fast with increasing V_a. Figure 3 illustrates this process. Before the invention of the germanium and silicon diode, it was common to use valve diodes to rectify AC to DC, but because of their higher resistance they had larger power losses than modern silicon rectifier circuits. Therefore, the valve diode is also often called a rectifying valve.



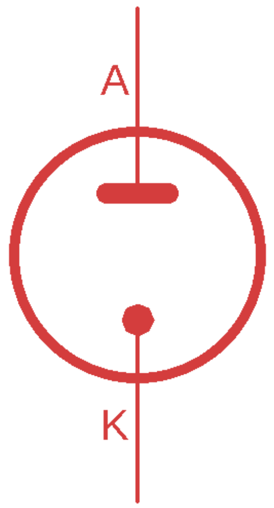


Figure 1: Symbol for a valve diode used in schematics. The circle represents the glass envelope. Anode A and Kathode K. The Heater filament is commonly omitted since it is seperate component in an indirectly heated valve which should always be connected to an appropriate power source specified by the data sheet[7].

Figure 3: I_a in relation to V_a from a GZ34 from 1954. The Diagram is taken from the Philips data sheet of the GZ34. One GZ34 but two independent anodes, therefore there are actually two valve diodes with a common cathode in the glass envelope of a GZ34. The curve is visibly not linear and therefore the diode is not an ohmic resistor as the resistance decreases as V_a increases[8].

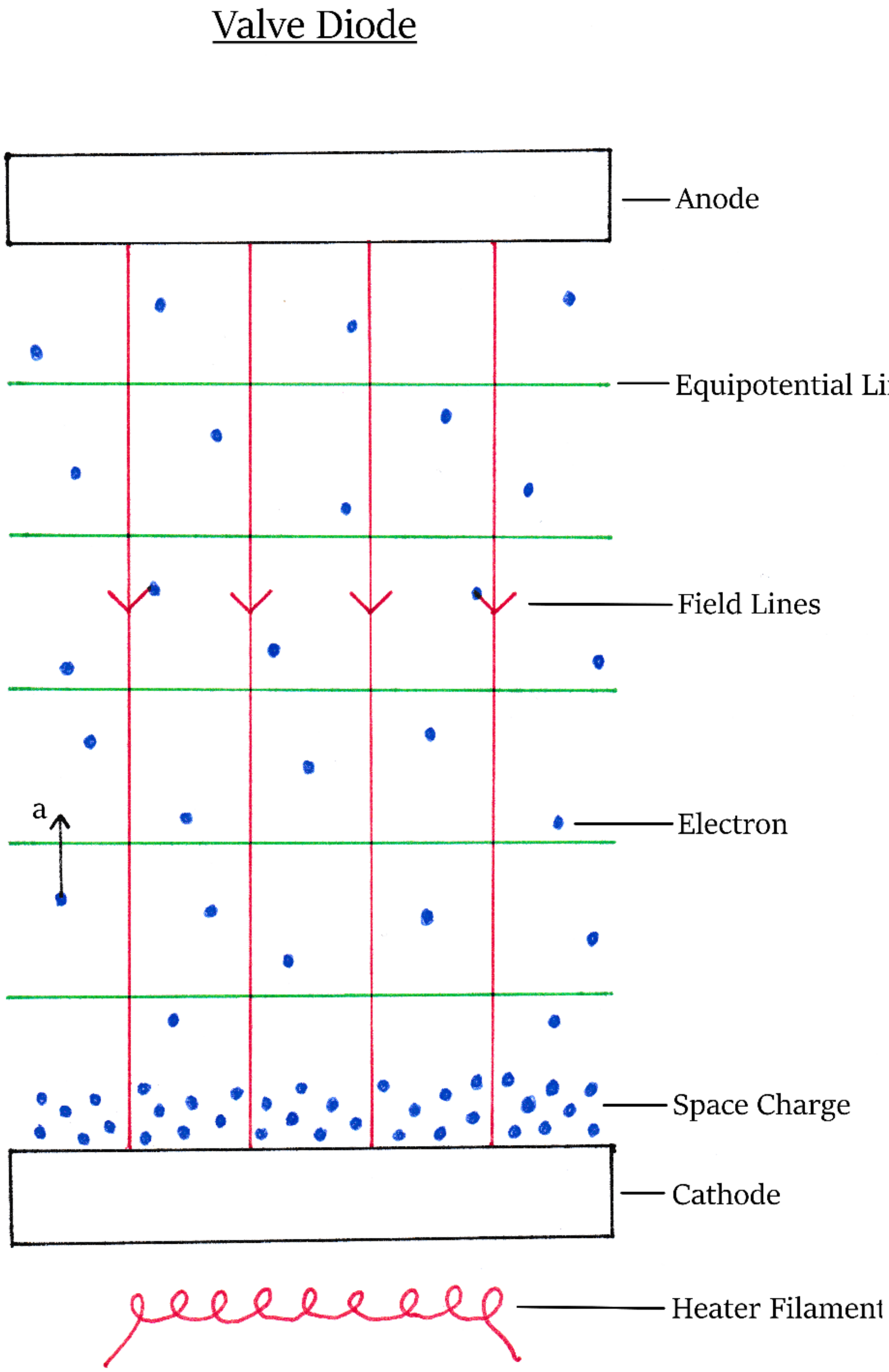


Figure 2: Qualitative sketch of the process inside a working valve diode. The anode is at a higher electric potential than the cathode thus electrons from the space charge are accelerated towards the anode. A indicates the direction in which the electrons are accelerated.

Valve Triode

If a valve diode is connected to a circuit providing a constant V_a, there will be a constant I_a. To control the current through the valve, like its name suggests, a simple diode is therefore not enough. The triode, initially called audion, invented by Flee de Forest in 1906[9], adds a third electrode to the design of a diode. This third electrode is called the control grid, it is a metal mesh between the anode and the cathode. In schematics, the valve triode is pictured as seen in Figure 4. By changing the voltage V_g of the control grid, I_a can be controlled. If V_g is negative, the control grid will repel the electrons from the cathode, but, as the grid is not completely solid, there are still some paths where the electrons get attracted by the anode. Further decreasing V_g will increase the effect of the electric field of the grid, making the pathways for the electrons smaller until they are completely blocked and there is no current through the valve anymore. The state of a valve when there is no I_a is called cut-off. As the control grid is much closer to the cathode than the anode is, a V_g of small magnitude can compensate for a V_a of much greater magnitude. Since V_g changes I_a it is very useful that indirect heating allows to set the voltage between the cathode and ground independently of supply voltage of the heater filament. Figure 5 illustrates this process qualitatively.

The current through a triode is therefore dependent on two parameters: V_a as well as V_g. A diagram, called the plate characteristics, commonly found in the datasheet of a valve triode allows to determine I_a for a given combination of those two parameters. The plate characteristics look similar to the diagram with the specifications of a valve diode. Yet, the plate characteristics contain multiple graphs, each describing how I_a changes with V_a for a given V_g. These graphs are called the grid curves. Figure 6 shows the grid curves of a still widely used triode: The ECC83.

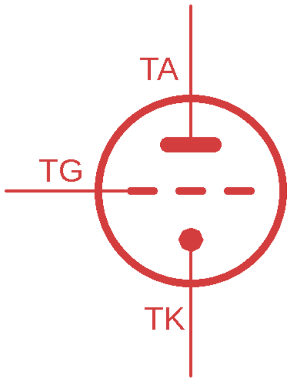


Figure 4: Symbol for a valve triode used in schematics. Anode A, gcontrol grid TG and cathode TK. Like in the symbol of a valve diode, the heater filament is not shown[7].

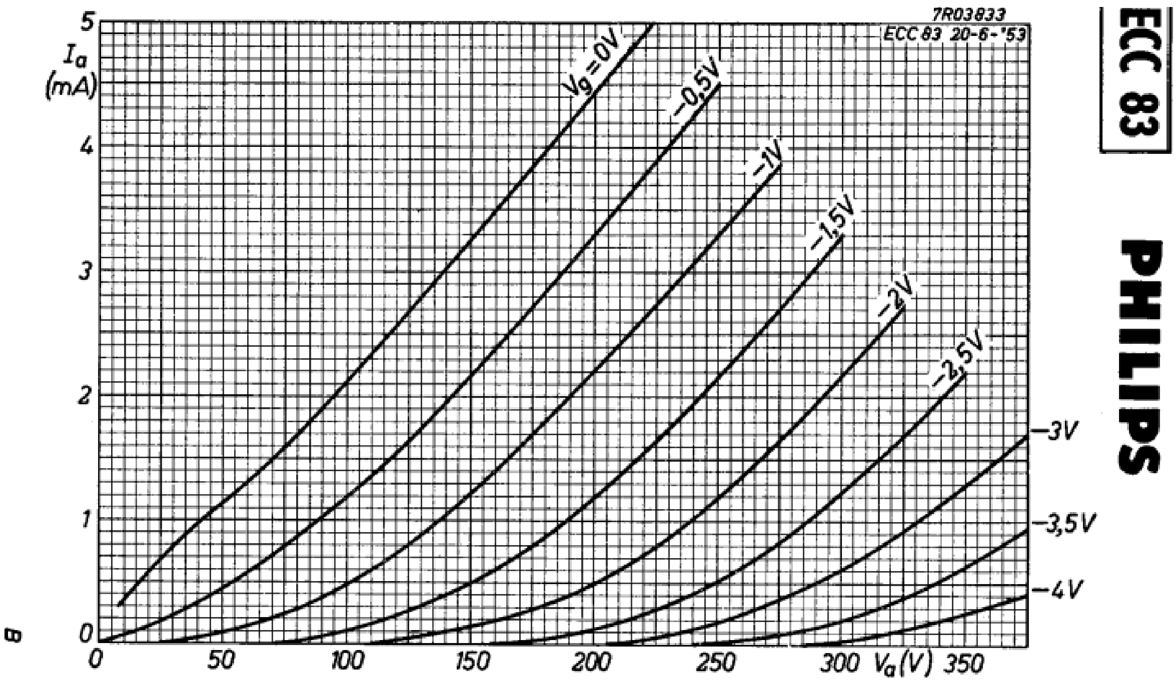


Figure 6: Grid characteristics of an ECC83, also called 12AX7 or 7025, taken from the Philips data sheet. The ECC83 double triode, which means there are two completely independent triodes in one physical ECC83[4].

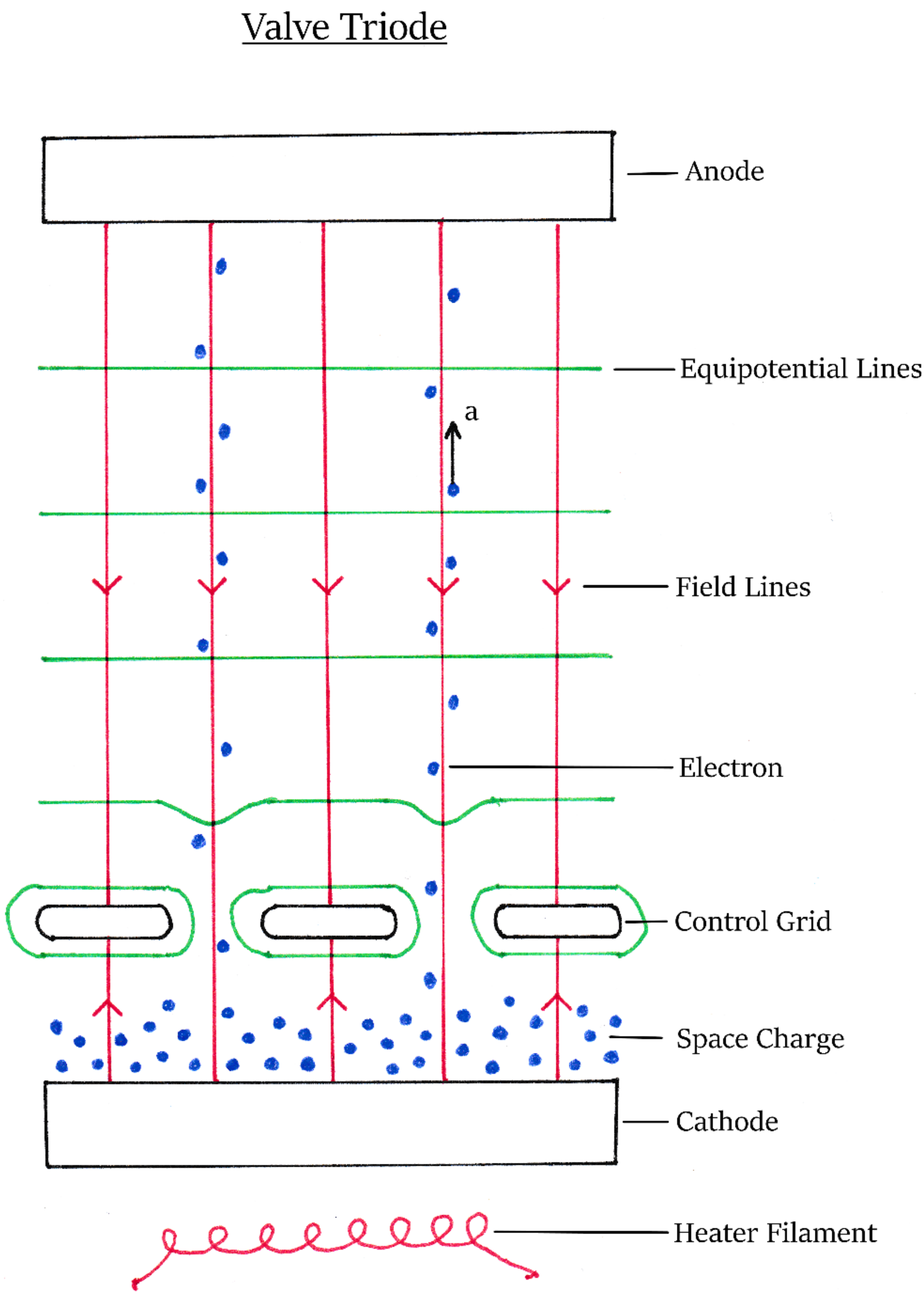


Figure 5: Qualitative sketch of the process inside a working valve triode. The negative V_g restricts the flow electrons.

Signal Amplification with a Triode

Assuming $V_g = -1.5V$ and $V_a = 250V$. If an AC voltage signal V_{in} with an amplitude of 0.5V is now superposed on Vg, I_a will follow V_g, like shown in Figure 7.

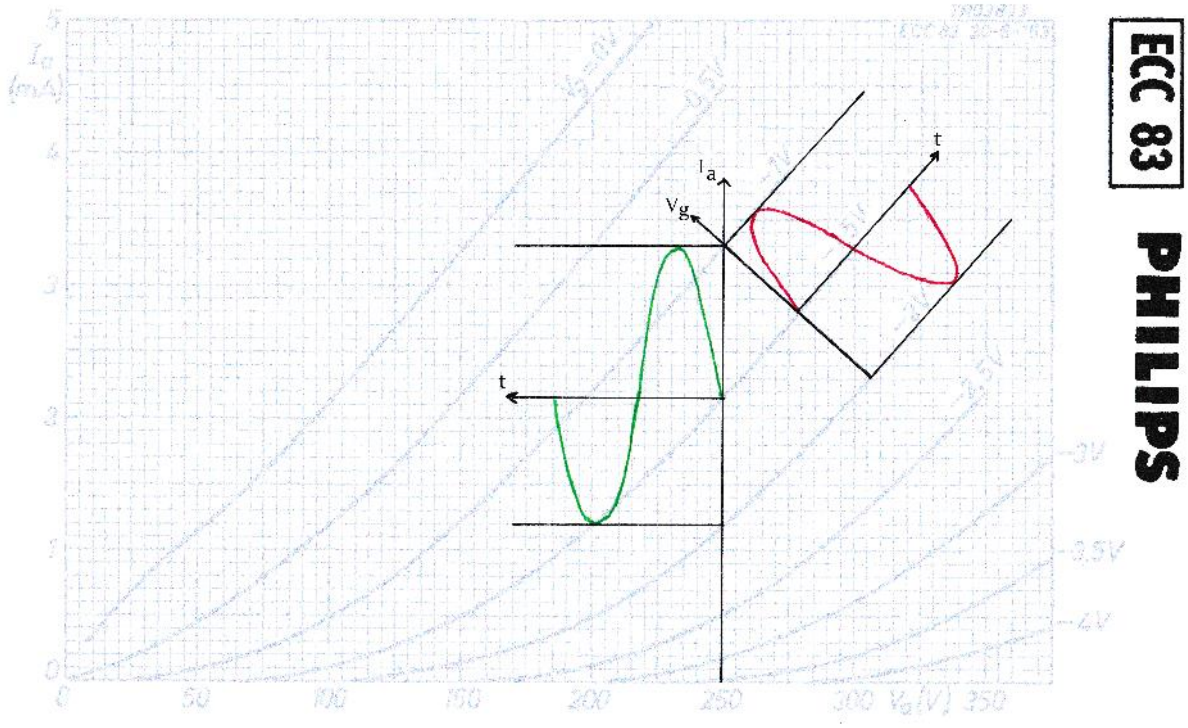


Figure 7: A modified version of plate characteristics of an ECC83. The altering V_g (red) causes I_a (green) to follow it[4].

Assuming now there is a resistor R_a (anode resistor) connected in a circuit between the supply voltage HT^+ and the anode. Ohm's law states that current passing through resistance creates voltage across it, so V_a will change dependently on I_a.

$$V_a = HT^+ - (I_a \cdot R_a)$$

However, as mentioned before, I_a itself is dependent on V_g as well as V_a. The most practical way to determine the resulting situation is the construction of the load line[2]. The load line contains every possible point (V_a/I_a) for a given HT^+ and R_a. The load line is a straight line which can easily be drawn into the plate characteristics diagram by determining the two extreme points: $V_a = 0$ and $I_a = 0$.

If: $V_a = 0$ then follows: $I_a = \frac{HT^+ - V_a}{R_a} = \frac{HT^+ - V_a}{R_a} = \frac{HT^+}{R_a}$

If: $I_a = 0$ then follows: $V_a = HT^+ - (I_a \cdot R_a) = HT^+ - (0 \cdot R_a) = HT^+$

Therefore, the two extreme points of the load line are $(0/\frac{HT^+}{R_a})$ and $(HT^+/0)$

Note that the point $(0/\frac{HT^{+}}{R_a})$ is only hypothetical as the valve is not able to conduct current without any resistance. Nonetheless, it helps to draw the load line. Connecting the two extreme points with a straight line results to the load line. Be $HT^{+} = 250V$ and $R_a = 100k\Omega$. In the example, the two extreme points are: $(0/2.5mA)$ and $(250V/0)$.

Superposing like before V_{in} on V_g will now lead to an AC voltage signal V_{out} being superposed on V_a. As the voltage across R_a increases as V_g does, V_a decreases when V_g increases. Therefore, V_{out} is inverse to V_{in}, reaching its negative peak when V_{in} does reach its positive peak and vice versa. Figure 8 illustrates this process.

The ratio of V_{out} and V_{in} is the amplification factor called gain. It is not uncommon for the gain to be written as a negative number, as V_{out} is, as mentioned, inverse to V_{in}, yet the positive notation is preferred in practical applications. This circuit is called a common cathode gain stage and is the most common and basic type of valve circuit for small signal amplification. Figure 9 is the schematic of a basic common cathode gain stage[2]. Understanding the concept behind the valves, however, also allows for different configurations which might be better suited for more specialized applications.

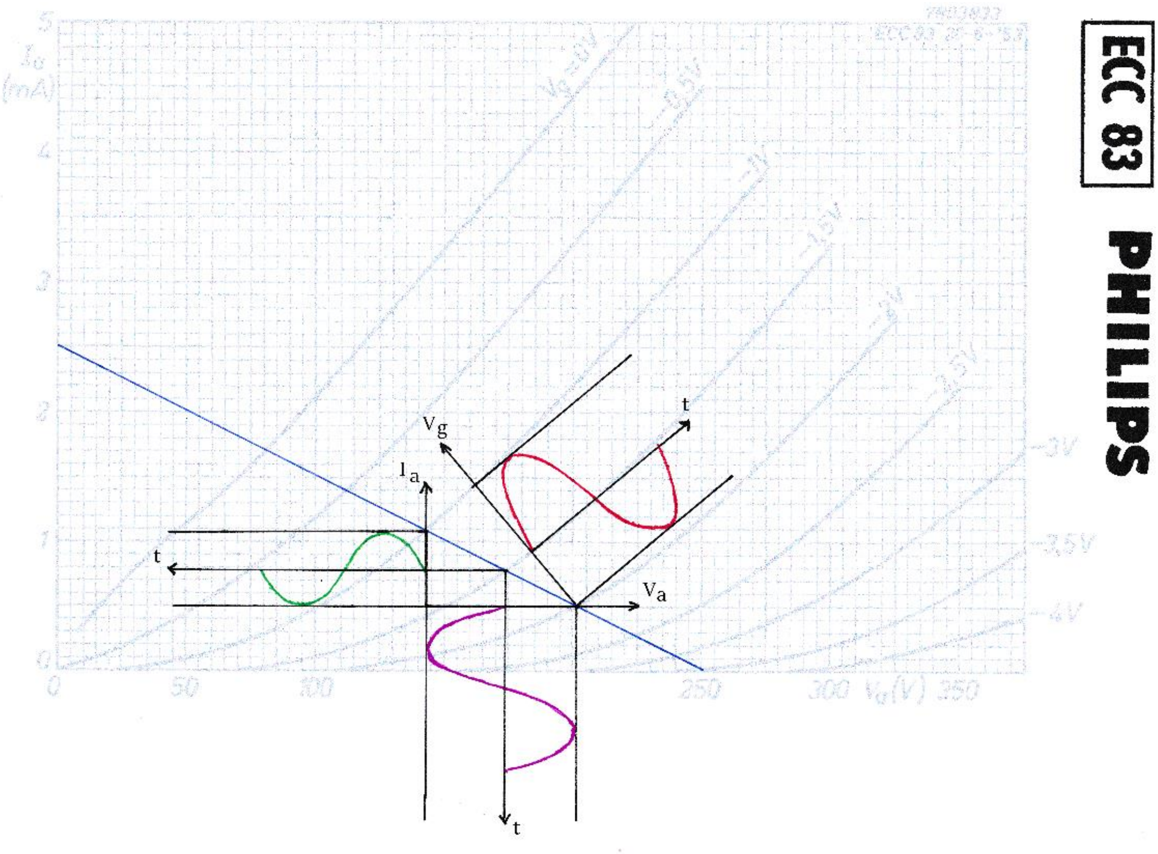


Figure 8: Load line (blue) for $HT^{+} = 250V$ and $R_a = 100k\Omega$ drawn into the plate characteristics of an ECC83. The AC component V_{in} of V_g (red) has a peak-to-peak voltage (Vpp) of 1V. The AC component V_{out} of V_a (violet) has a Vpp of 58V. Thus, the gain of this circuit is 58[4].

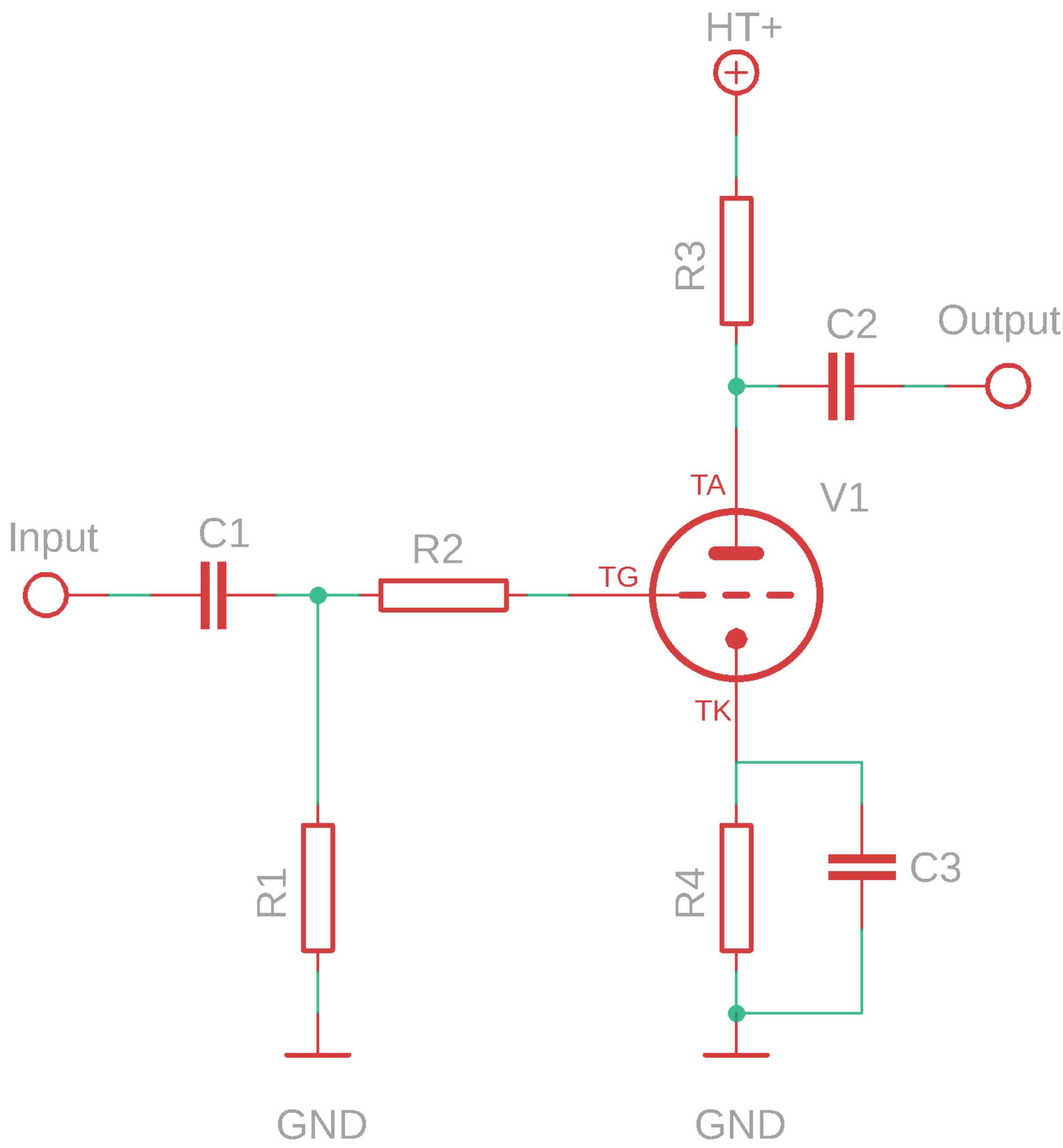


Figure 9: Schematic of a basic common cathode gain stage.
C1: input coupling capacitor, R1: ground reference resistor, R2: grid stopper reisistor, R3: anode resistor, V1: valve triode, R4: cathode resistor, C2: output coupling capacitor and C3: cathode bypass capacitor. The purpose of R1, R2, R4 and C3 will be explained later.[7]

Distortion and Clipping

Ideal amplification is the exact reproduction of the input signal with only changing the amplitude by a constant factor. If the output signal differs otherwise in from the input signal, it has not only been amplified, but also distorted. There are three different ways how the signal can be distorted by a valve gain stage.

The first kind of distortion is unavoidable and is caused by the uneven spaces between the grid lines. This is already apparent in the Figure 8, while V_{in} was symmetrical, with V_g oscillating ±0.5V around -1.5V, V_{out} is asymmetrically distorted, with V_a oscillating +27V/–31V around 174V.

The other two kinds of distortion happen if the amplitude of V_{in} is too great. They only affect the peaks of V_{out} and are clipping distortions.

If V_g gets so negative that the valve reaches cut-off, further reducing V_g will not change I_a, since it is already zero. Therefore, V_{out} is not able to follow the negative peaks of V_{in} and the waveform of V_{out} will look like its positive peaks have been clipped off. Since this clipping distortion happens because the valve reaches cut-off, it is called cut-off clipping[2].

If V_g becomes positive, electrons will impact on the control grid and lead to the grid current I_g. I_g increases V_g. As seen in figure 9, it is common practice to place a resistor R_g (grid stopper) in front of the grid. R_g avoids self-driven oscillations of the valve but also protects the grid from a too high V_g and thus high I_g, which could lead to overheating, also called over dissipation, of the grid. I_g creates a voltage across R_g. As the electrons flow out of the grid, I_g flows into the grid, reducing V_g. Therefore, V_g will not be a superposition of a DC component and V_{in}, but a distorted version of V_{in}, whose positive peaks have been attenuated I_g and R_g. V_a will follow V_g and thus the negative peaks of V_{out} will look compressed. This distortion is known as grid current clipping and it is dependent on the size of R_g, as a bigger resistance leads to a higher voltage and therefore more compression of the negative peaks of V_{out} but generally speaking is grid current clipping a less drastic effect than cut-off clipping. Omitting R_g would eliminate grid current clipping, but then V_{out} would just be distorted by the nonlinear operation of a valve at $V_g > 0V$. Additionally, without R_g the valve is not protected against self-driven oscillation or grid over dissipation anymore, therefore R_g is heavily recommended[2].

Bias

The DC component of V_g is also called the bias. It determines the threshold of V_{in} above which clipping occurs. This is also called the headroom of the gain stage. For maximal headroom, the optimal bias equals half of the V_g which causes cut off. Therefore, the bias for optimal headroom in Figure 8 would be $\frac{3.5V}{2} = -1.75\text{V}$. If the headroom does not have to be maximal, since V_{in} has a known small amplitude, the bias can be set to a higher value. Since the grid curves for higher values of V_g are further apart than the ones for low values of V_g, this will increase the gain of the circuit. If V_{in} is meant to be clipped by the gain stage, which is also called overdriving the gain stage and will become more important when talking specifically about guitar amplifiers, the bias can also be used to intentionally decrease the headroom and choose which clipping occurs first. This is important, as due to their different intensities, the two kinds of clipping sound different.

Regarding bias there are two important terms: hot and cold bias. A hot bias refers to relatively high bias voltage and thus high I_a. A cold bias is the opposite where the bias voltage is rather low and the I_a low as well. There is no exact definition at which point a bias is considered hot or cold. These expressions are commonly used context dependent and relative rather than absolute.

In a valve circuit there are multiple ways to apply the bias. The two most common methods are called fixed bias as well as cathode bias. In a fixed bias circuit, the bias is applied by a negative voltage source at the grid with the cathode connected to ground. Often, this is done with a trim potentiometer wired as a voltage divider, thus the voltage can exactly be adjusted. In a cathode biased circuit, like the one pictured in figure 9, the grid is commonly connected to ground by a resistor and the bias is applied by increasing the voltage between cathode and ground. If a resistor R_c: the cathode resistor is placed between cathode and ground I_a will create a voltage across R_c, V_{Rc}.

$$V_{R_c} = I_a \cdot R_c$$

With the grid connected to ground this will result in $V_g = -V_{R_C} + V_{in}$.

When a signal is amplified, V_{Rc} will not be constant anymore, as it changes together with I_a. Therefore, V_g will change inversely to V_{in} and attenuate it to some extent. This effect is called negative feedback and it has its advantages as well as disadvantages. While negative feedback reduces the overall gain of the circuit, it provides more stability and decreases the impact of deviations between two valves of the same type. In fact, negative feedback is still heavily used in analogue transistor circuits. As the deviations between two transistors of the same type can be very big, negative feedback is necessary to build reliable and predictable circuits. To avoid the negative feedback and maximize the gain of the circuit a capacitor: cathode bypass capacitor, C_c, can be added in parallel with R_c. As the impedance of a capacitor changes with frequency, a sufficient enough capacitor will result in minimal impedance for AC signals and will eliminate negative feedback. This configuration is called a fully bypassed gain stage. A smaller capacitor will lead to frequency dependent negative feedback. This can be useful if one wants to amplify higher frequencies with maximal gain while reducing the gain for lower frequencies through increasing negative feedback[2].

Valve Pentodes and others

Another important type of valve is the pentode, which adds two further electrodes to the triode architecture: the screen grid and the suppressor grid. A valve pentode is represented in a schematic by the symbol in figure 10. The screen grid is between the control grid and the anode. The voltage V_{g2} of the screen grid, is commonly in the order of magnitude or even greater V_a. Therefore, it is now the screen grid which mainly accelerates the electrons emitted by the cathode towards the anode, as it is closer to the cathode than the anode. This causes the grid curves to be shaped differently compared to a triode and I_a being much less dependent on V_a, given it is above a certain threshold. Different values of V_{g2} result in different grid curves, therefore a pentode has not only one plate characteristics diagram with multiple grid curves, but it is possible to draw different plate characteristics diagrams for every V_{g2}[2]. Figure 11 shows possible plate characteristics for an EL34.

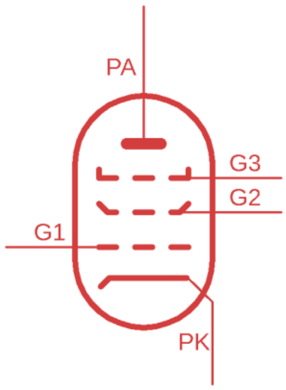


Figure 10: The symbol for a valve pentode used in a schematic. With the anode, PA, the suppressor grid, G3, the screen grid, G2, the control grid, G1, and the cathode, PK. Again the heater filament is not shown in the symbol[7].

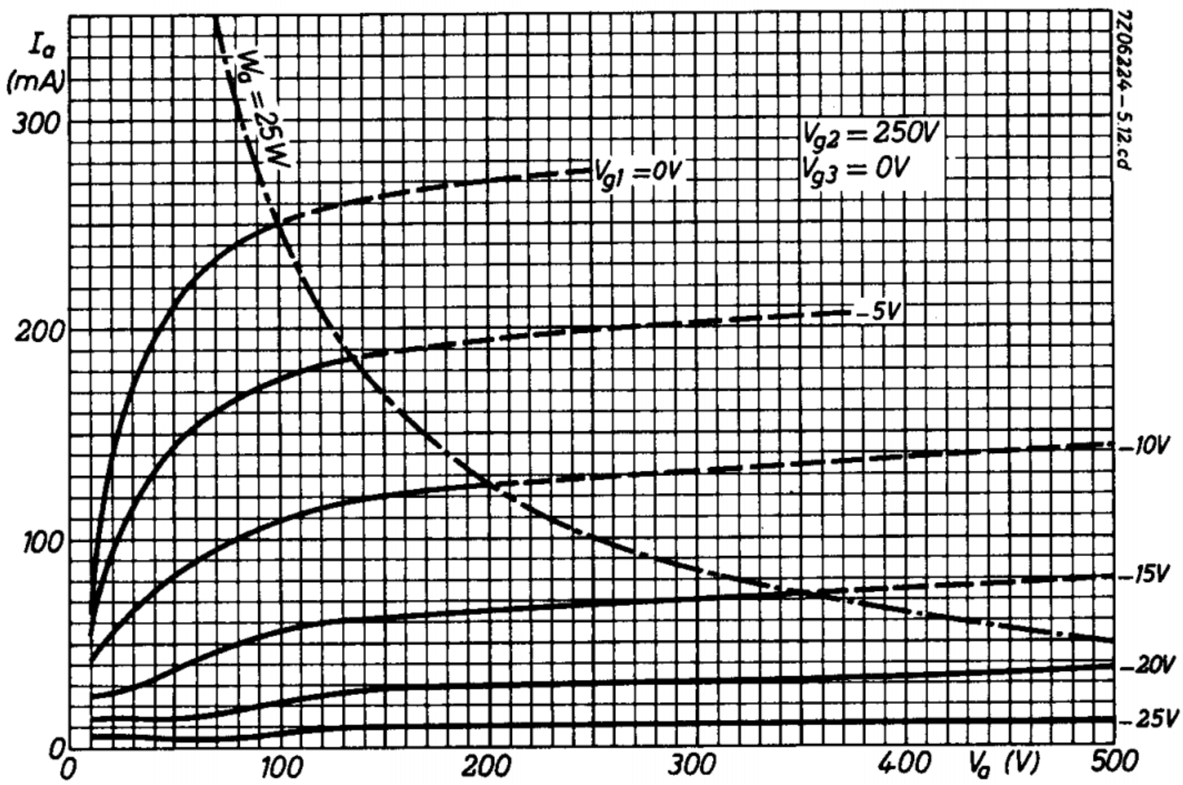


Figure 11: Plate characteristics of an EL34 specified by the Philips data sheet. These are the plate charactersitcs for $V_{g2} = 250V$ and $V_{g3} = 0V$ the data sheet contains informations to approximate the plate characteristics for other values of V_{g2}[5].

The existence of the screen grid yields another benefit. It shields the anode from the grid, which eliminates the capacitance between those two. This capacitance is undesirable, since it connects the output with the input. At high frequencies, such as radio signals, the impedance of this capacitance becomes small enough that the output and input signal interact with each other, creating a so-called feedback loop. As the output signal is an inverse of the input signal, it is negative feedback reducing the gain of the circuit. By eliminating this capacitance and therefore the feedback loop, pentodes can amplify high frequencies without loss of gain[2].

The existence of a second grid, which is like the anode at a positive voltage, yields, however, a problem. The impacting electrons on the anode can cause some electrons of the anode to be emitted again, this is called the secondary emission, and these electrons could then be also attracted by the screen grid. To avoid this a fifth, electrode the suppressor grid is added between the screen grid and the anode. The suppressor grid is commonly at the same electric potential as the cathode, $V_{g3} = 0$, so that the secondary emission electrons cannot be attracted by the screen grid anymore and return to the anode. The electric fields between the screen grid and the suppressor grid slow the electrons down after they passed the screen grid, however, they are so fast at this point, that they are just slowed down but cannot change the direction anymore. Figure 12 qualitatively illustrates the process in a working valve[2].

Another common type of valve is the beam tetrode. It works with the same principle as a pentode, with some slight changes in the design. There do exist also other, more specialized, types of valves, however, the four here introduced are the ones most common and important ones and are still produced to date.

Small Signal and Power Valves

Besides the different types of valves, one has also to distinguish between small signal valves and power valves. Small signal valves also called preamplifying valves, short: preamp valves. They are only intended for voltage amplification and they conduct very little current. The ECC83 is a preamp valve and, as seen in the example from before, I_a is only a few mA. Power valves are, as their name implies, intended for power amplification. They have a certain voltage gain, but I_a in a power valve is much higher than in a small signal valve. In a circuit with a power valve, there is no R_a; instead, there is a load receiving the power, such as a transformer, which is coupled to a loudspeaker or an antenna of a transmitter. Commonly, a complete amplifier circuit needs both types of valves as the input signal is too small to be directly amplified by the power valves, therefore they need to be preamplified by the preamp valves.

Valve Pentode

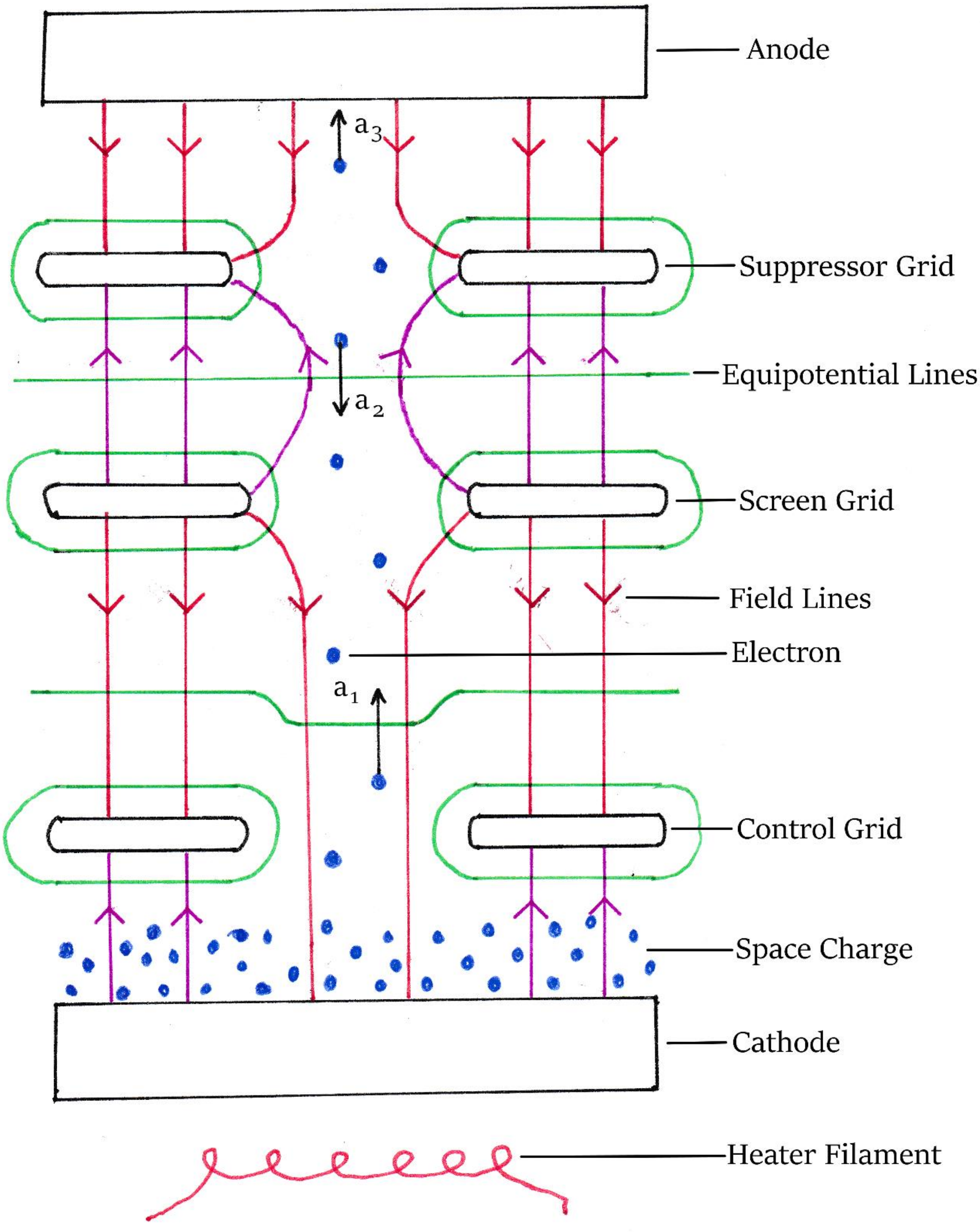


Figure 12: Qualitative sketch of the process inside a working valve pentode. The electrons are now accelerated by the voltage of the screen grid. The voltage oft he suppressor grid is 0V ensuring secondary emissions are less likely to impact on the screen grid. A_1, a_2 and a_3 indicate the direction in which the electrons are accelerated at this position. As the direction of the electric field changes, so does the direction of acceleration.

2.3 Guitar Amplifier Theory

Pre- and Power Amp

Whether a guitar amplifier is built with valves, transistors or a combination of both, it can almost always be divided into two different amplifier sections: the preamp and the power amp. The purpose of the preamp is to modify and shape the guitar signal. It doesn’t matter if it is distorted rock or clean Jazz, which is played, the raw signal from the magnetic pickups of the guitar need to be shaped and filtered in a certain way to sound pleasant. Without any equalizing by the preamp the guitar would sound dull, lifeless and muddy. The signal from the preamp gets then passed to the power amp, where it is amplified to the desired power level. The output power of a guitar amplifier can range from a few watts for home use up to a hundred watts or, in some exceptions even more, which are played at big concerts.

The standard controls most modern guitar amplifiers offer are the following five: Gain, Bass, Middle, Treble and Volume. The Gain control adjusts the volume in the preamp. Increased volume in the preamp leads to distortion, also called overdrive, which is in the case of guitar amplifiers often desirable. Therefore, the gain control should best be regarded as a distortion control. Turning it up will increase distortion, turning it down will decrease the distortion. Bass, Middle and Treble are the equalization controls of the preamp. How these three frequency bands are defined differs between different amplifiers, However, it can be roughly said that bass frequencies are the ones below 300Hz, treble frequencies the ones above 1.1kHz and the middle frequencies are the ones in between. In most amplifiers, those three controls work not like a Hi-Fi or studio equalizer, as most amplifiers have a passive equalization circuit, called tone stack. Therefore, the controls are highly interactive and do not operate linearly. While many people might think of this as a bad thing, this is not necessarily the case, since the characteristics of certain tone stack circuit add much to the individual sound of a guitar amplifier. Finally, the volume controls the volume of the power amp and thus the volume of the whole amplifier.

Special Features

Many guitar amplifiers offer additional features, such as different switchable channels with different amounts of distortion, inbuilt effects such as reverb or vibrato, an effects loop, fx-loop, which allows to connect external effects such as delay, reverb or tremolo etc. between the preamp and the power amp or resonance and presence controls which affect the volume of the very low and very high frequencies in the power amp.

Guitar Amplifiers and Valve Distortion

The reason why many guitar players still prefer valve amplifiers to the ones built from transistor has many different aspects. First do many people think that valve amplifiers just sound much better than transistors. Many people associate a warm and responsive sound with valves, whereas transistors are said to sound sterile or harsh. This may be due to the bigger nonlinearities of valves compared to transistors. Similar things are also said about the distortion produced by valves compared to the distortion caused by clipping diodes, which are often used in transistor amplifiers.

Lastly, one has also to acknowledge that most guitar players can be very nostalgic if not fanatical. Valve amplifiers gave birth to the electric guitar and rock and roll music. The most iconic records from famous bands such as The Beatles, Jimi Hendrix, Led Zeppelin or Black Sabbath have been played on loud, heavy and hot valve amplifiers. Therefore, valve amplifiers have something magic and fascinating to them for most guitar players.

British and American Amplifier Sounds

When describing the sonic qualities of guitar amplifiers, the term British or American sound is often used. This refers to the difference between early and iconic guitar amplifiers from the respective country. American amplifiers by Fender had lots of bass and treble frequencies, sounded very clean and are associated with jazz or blues, whereas the British amplifiers by Marshall had more midrange frequencies, sounded more aggressive and distorted and are thus associated with rock ‘n’ roll and rock. As these terms are only historically defined there are nowadays also amplifiers from American manufacturers which have a British sound to them as well as British amplifiers which sound American.

3. The amplifier

3.1 Overview

After countless hours spent studying theory, crafting an enclosure, drawing schematics, soldering and optimizing parts of the circuit, the amplifier, centrepiece of this Matura project, was finally completed. Its name: GNR-50. It can be seen on figure 13, figure 14 and figure 15.

The GNR-50 runs on two ECC83 preamp valves and two EL34 power valves. It offers two distinct modes: gentle and raw. While operating in gentle mode, the sound of the amplifier can be adjusted by all six control knobs on the front plate. The master volume adjusts the overall volume of the amplifier. Although the gentle mode is the clean channel of the amplifier and therefore does not have any distortion, the gain control is far from useless. Increasing the gain will lead to thicker sound, while decreasing it will clear it up. The four controls of the tone stack offer much customizability. Bass, Middle and Treble do what their name suggests. However, at the core of the tone stack is the voice control. It changes the range and reaction of the three other tone controls. Turning the voice knob counter clockwise will give the GNR-50 some British grunt, while turning the control clockwise will add some American sparkle. When entering raw mode, tone stack gets deactivated and the amplifier can provide some gnarly overdriven tones.

The two EL34 can put out up to 50 watts of power and are cathode biased, which allows for a power valve exchange without the need to readjust the bias of the power section. Additionally, the GNR-50 offers a serial fx-loop and an impedance switch to match 8Ω or 16Ω speaker setups.

Figure 13: The finished GNR-50.

Figure 14: The front of the GNR-50.

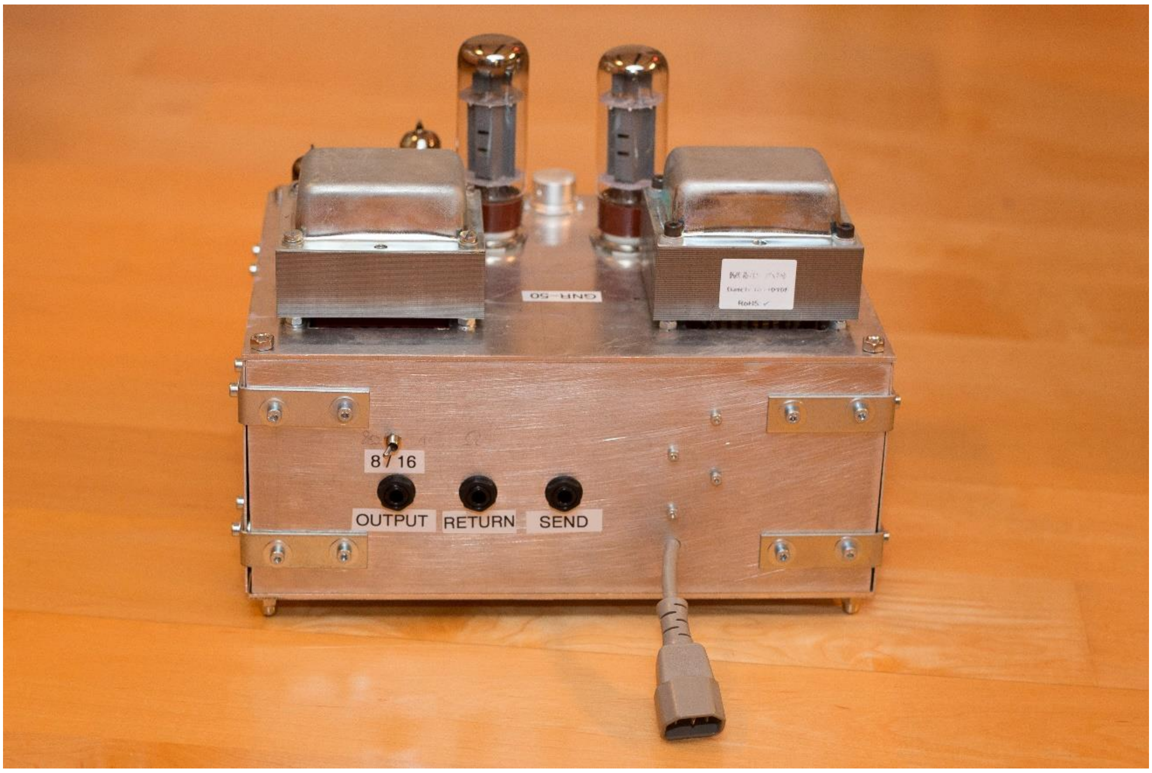


Figure 15: The back of the GNR-50.

3.2 Circuit analysis

Figure 16 and figure 17 show the complete schematic of the circuit of the GNR-50 without the power supply. The circuit can be divided into six stages: The input stage, the tone stack and the fx-send stage, which form the preamp and the fx-return stage, the phase inverter stage and the power stage which belong to the power amp. The following pages provide a more in-depth description of every section whilst also explaining the importance and function of the key components.

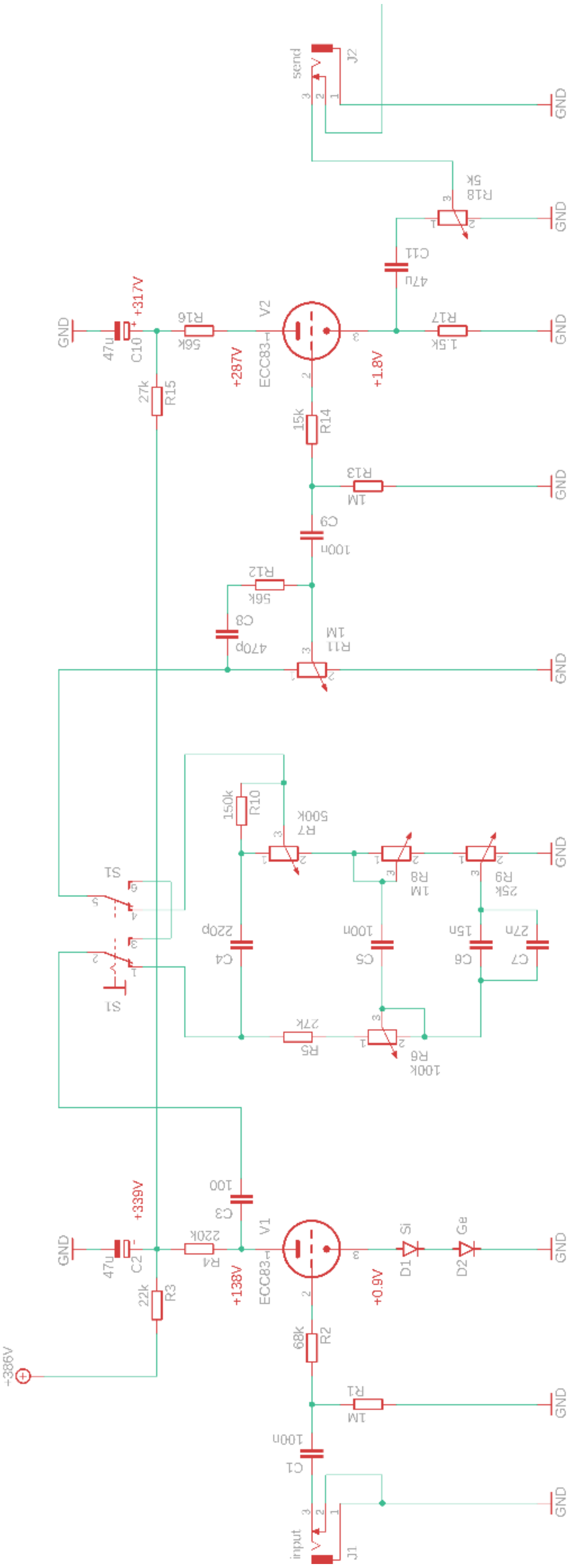


Figure 16: Schematic of the preamp section of the GNR-50[7].

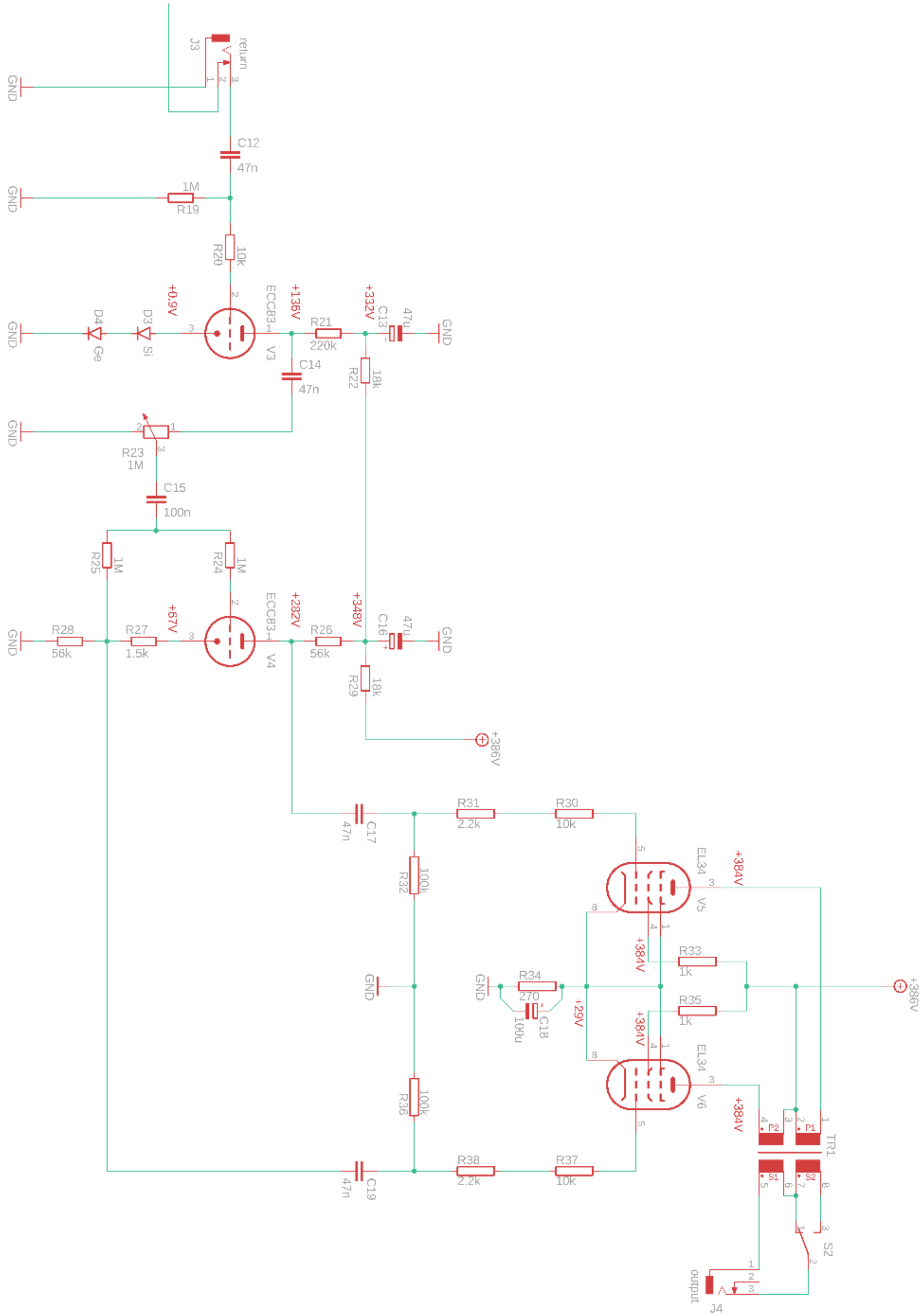


Figure 17: Schematic of the power amp section of the GNR-50[7].

Power Supply

Since the power supply can be considered not to be a part of the actual valve amplifier but just a given necessity, it is not depicted in the complete schematic and has its own numbering scheme. Figure 18 shows the schematic of the power supply. Its centrepiece is the mains transformer TR1. A transformer consists of an iron core and two coils called the primary and the secondary windings. Through induction, a transformer can transform an applied AC voltage V_p at the primary to another AC voltage V_s of the same frequency at the secondary. The ratio of the two voltages depends on the ratio of the number N of turns in the primary's and secondary's windings. For an ideal transformer applies[6]:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

An ideal transformer has no power loss, thus the following expressions can be derived:

$$P = V \cdot I \rightarrow I = \frac{P}{V} \rightarrow I \propto \frac{1}{V}$$

$$\frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Therefore, a transformer can also be regarded as a device which scales the impedance Z_s connected to the secondary to an impedance Z_p at the primary.

$$\frac{Z_s}{Z_p} = \left(\frac{N_s}{N_p}\right)^2 \rightarrow Z_p = Z_s \cdot \left(\frac{N_s}{N_p}\right)^2$$

TR1 transforms the 230VAC 50Hz mains voltage to 300VAC 50Hz, 25VAC 50Hz and 6.3VAC 50Hz. To accomplish this, it has not only one but three individual secondaries.

300VAC gets rectified by the silicon full bridge rectifier B1 and charges the reservoir capacitor C2. It acts as an energy buffer and keeps the DC voltage steady. When the mains voltage is at its peaks it charges C2. Between the peaks of the mains voltage, the capacitor discharges and provides energy to the amplifier. The larger the reservoir capacitor, the lower the fluctuation, ripple, of the DC voltage in the amplifier. C2 has a capacitance of 680uF, which is a very good value for a guitar amplifier. The negative side of C2 is connected to the ground and the positive side is the power supply for the HT^+ of the all the valves in the amplifier. To further reduce ripple, all the ECC83 gain stages are not connected directly to C2, but the current flows through low-pass filters, which reduces any still existent ripple (figure 7: R3 and C2, figure 15: R15 and C10, figure 18: R22 and C13 and figure 19: R29 and C16). This will reduce the HT^+ of those stages, but this is not bad, since the voltage of C2 is by far enough for the ECC83s. The power stage, however, is connected directly to C2. As it is the very last stage, it is not as vulnerable to the hum from some ripple and the power stage does profit from a HT^+ as high as possible for maximal output. When the amplifier is turned off by disconnecting the primary through S1, the relay K1 closes switch K1. C2 gets discharged by R3. This was a feature necessary for safety during the building and testing process of the amplifier, as the high voltage stored in the capacitor could be lethal if touched.

The secondary, providing 6.3VAC, is connected to all the heater filaments of the valves. R1 and R2 set a reference to ground to minimize the hum which can be induced to the cathode by the filament. D1 and C1 form a DC voltage supply which connects to all indication LEDs and their series resistors of the amplifier. S2 is the standby switch. It allows the valves to first heat up for some seconds before the HT^+ is applied.

The third secondary is not pictured in the schematic as it is not used for the amplifier. It is assumed that the 25VAC are meant to be rectified and used as a supply for the bias of the power valves, but since they are cathode biased in the GNR-50, this is not required.

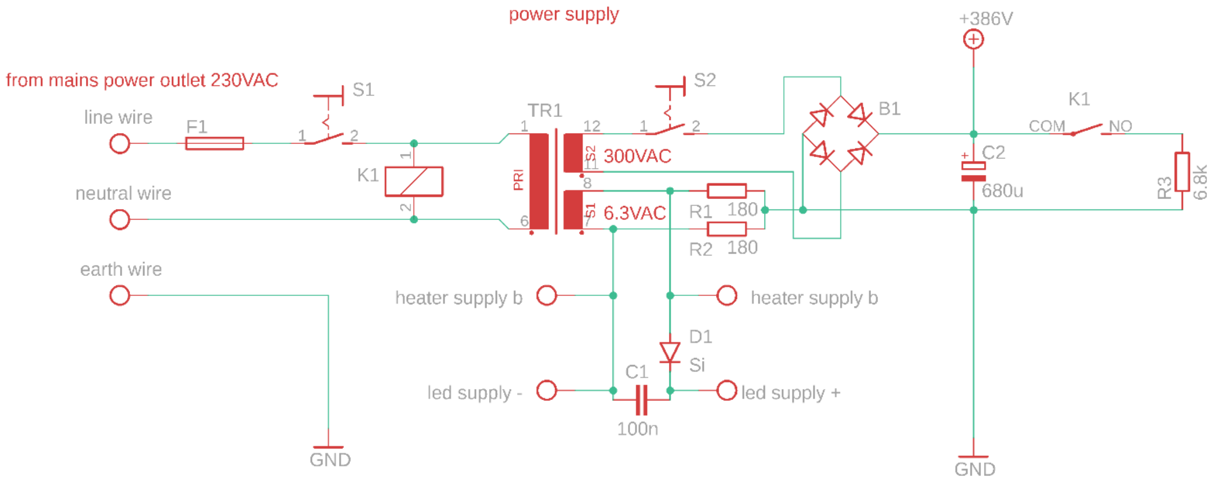


Figure 18: Schematic of the power supply of the amplifier[7].

Input Stage

The first stage of the amplifier is the input stage. Its schematic can be seen in figure 19. It receives the signal from the electric guitar plugged into it. Since the output of a pickup of an electric guitar is only a few hundred mV_{rms}, the input stage does not require great headroom. This allows for a hot bias to increase the gain and is also said to improve the sound of the stage. The bias is -0.9V and is provided by the diodes D1, D2 at the cathode, while the grid is connected to ground by R1. As diodes provide only negligible resistance, they do not add negative feedback, which would decrease the gain. The high value of R4 additionally increases the gain by causing a flat load line, as seen in figure 20.

A V_{in} with 1Vpp will cause a V_{out} of 75Vpp, therefore the gain of the Input stage is 75. However, this is only the case without an additional load. The input impedance of the tone stack respective the fx-return stage will load the input stage, causing the load line to rotate clockwise around the bias point and decrease the gain to some extent. The magnitude of this effect is dependent on the settings of the potentiometers in the tone stack and the gain control as they all influence the loading of the input stage.

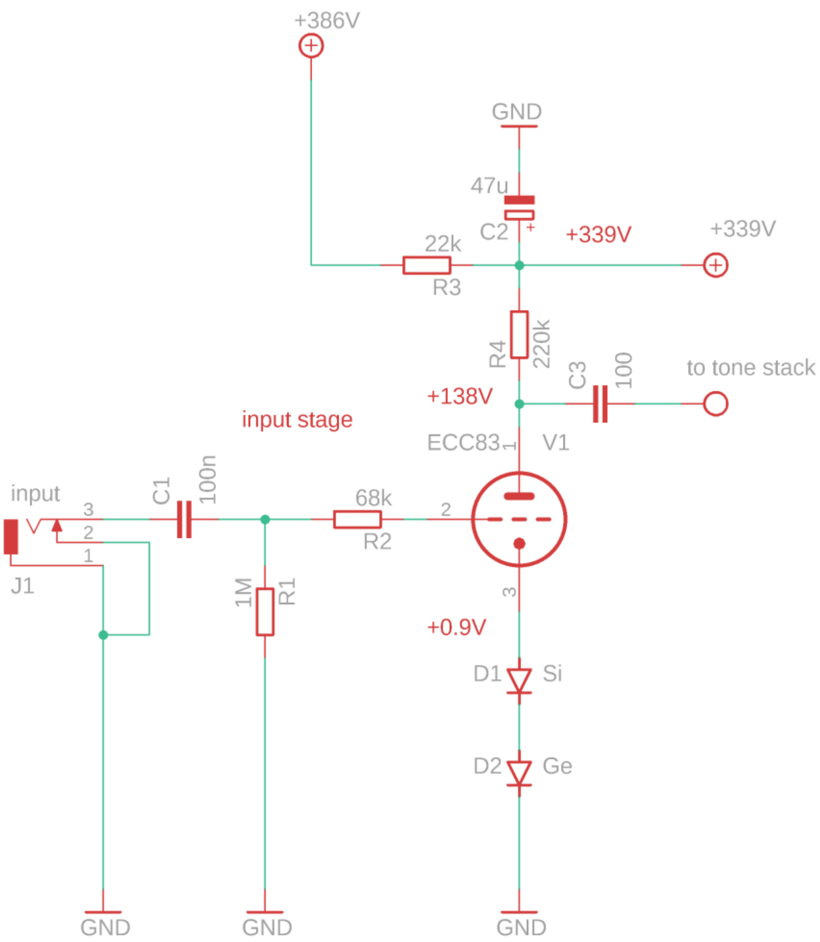


Figure 19: Schematic of the input stage[7].

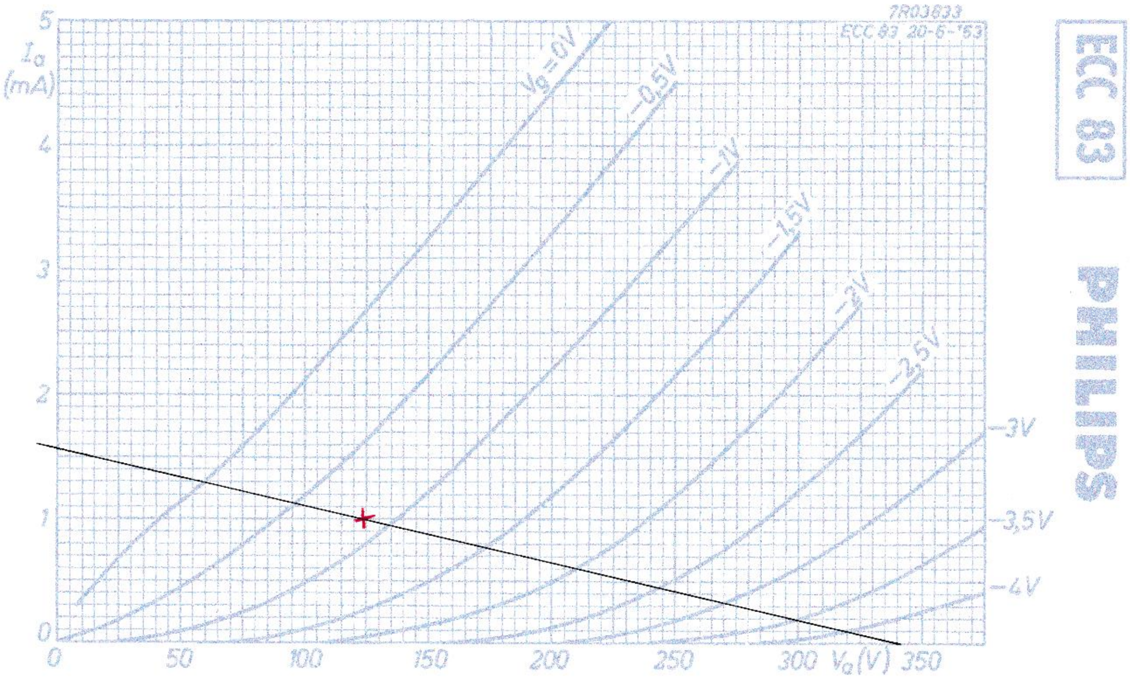


Figure 20: The load line (black) and the bias point (red) of the valve of the input stage V1[4].

Tone Stack

The tone stack is derived from the classic FMV circuit. FMV stands for Fender, Marshall, Vox, but this circuit is used in almost every guitar amplifier. Although the component values vary widely to give each amplifier its own voicing. The circuits main characteristic is that, with all three tone controls: bass, middle and treble are set to their middle position, the frequency response is not flat but, has a larger reduction in the midrange than the rest of the frequency spectrum. This so-called mid scoop creates a broad sound spectrum by emphasizing the bass and treble frequencies. By changing the component values of the circuit, the character of the tone stack can be drastically changed, however the mid scoop always remains to some extent. Figures 21 and 22 show two variations of the FMV tone stack and a simulation of their frequency response with all three controls set to middle position.

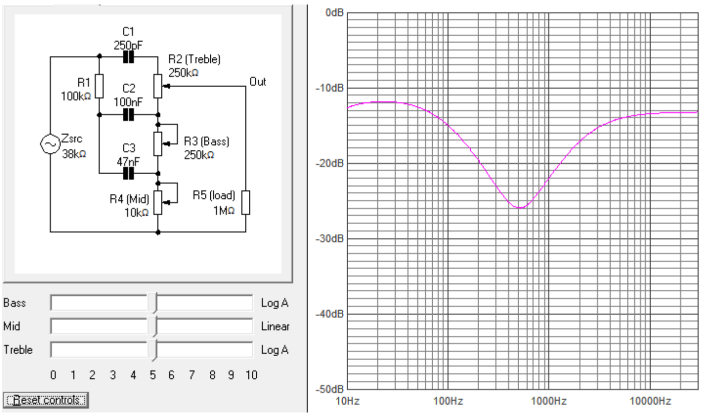


Figure 21: Tone stack and its frequency response of a Fender amplifier. Fenders are known for their large mid scoop, which gives them a very open and lush sound[10].

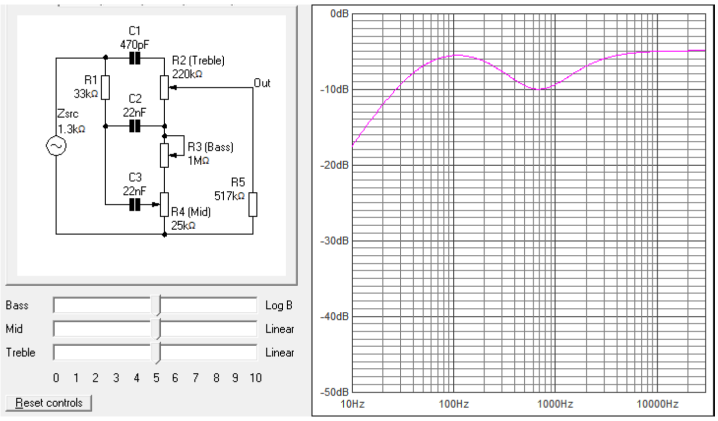


Figure 22: Tone stack and its frequency response of a Marshall amplifier. Compared to Fenders Marshalls have much more midrange which makes them sound more focues and present[10].

Although consisting only of a small number of components, the FMV is rather difficult to analyse, since it is a complex network of voltage dividers which also depends on the output impedance Z_o of the preceding as well as the input impedance Z_i of the following stage. Figure 23 is the schematic of the tone stack used in the GNR-50. The best way to understand the circuit is a qualitative approach. R6, C7 and R10 are modifications to the classic FMV circuit layout and should be ignored for the moment (R6 = 0Ω, C7 = omitted, R10 = omitted). R7 is the treble, R8 the bass and R9 the middle potentiometer.

For treble frequencies f_t, C4 provides only little impedance and R7 acts as a variable voltage divider. The connection from terminal 2 of R7 to ground through C5, C6 and R9 provides much less impedance for f_t than the connection through the R8 and R9, at least for most settings of R8. Therefore, the path through C5, C6 and R9 to ground completes the voltage divider circuit for f_t.

For bass frequencies f_b, C4 provides high impedance, therefore the voltage divider R7 is not of importance. R5 and C5, C6, R8 and R9 form a voltage divider. C6 does provide much impedance compared to the value of R9, therefore its position does not matter much. C5 provides less impedance and the resistance of R8 is much larger, thus its position heavily influences the attenuation of the voltage divider. R8 is a logarithmic potentiometer, which means it reaches around ten percent of its resistance in the first half of its sweep and the rest in the other half. A linear potentiometer would change the sound too abruptly.

For middle frequencies f_m, the impedance of C6 is comparable to the value of R9 and therefore it controls the attenuation of the voltage divider R5, C6 and R9. As R8 is much greater than R9 and in series to the whole resistance R9, the position of R8 does not affect the level of f_m much.

An effect which has now also to be considered is the voltage divider formed between Z_o and the tone stack as well as the tone stack and Z_i. As f_b and f_m always have to pass R5, a higher Z_o attenuates f_t more than t_b and t_m as long as Z_o is in the order of magnitude or smaller than R5.

The position of R7 does not only control the voltage divider for f_t, but also adds source impedance to f_b and f_m which forms another voltage divider with Z_i. Therefore, R7 does not act only like a treble control, but more like a blend knob between treble and all the lower frequencies.

The additional modifications do the following:

R10 decreases the attenuation of treble by the treble knob while still retaining the reduction of bass and middle frequencies by the added source impedance.

C7 was added after some testing and just adds up to the capacitance of C6, which changes the middle frequency band of the tone stack.

The voice control R6 adds to the resistance of R5. This alters the whole response of the circuit, changing the range of the frequency bands as well as the amount of mid scoop.

S1 completely bypasses the tone stack, which leads to the fx-return stage to be overdriven by the increase in volume.

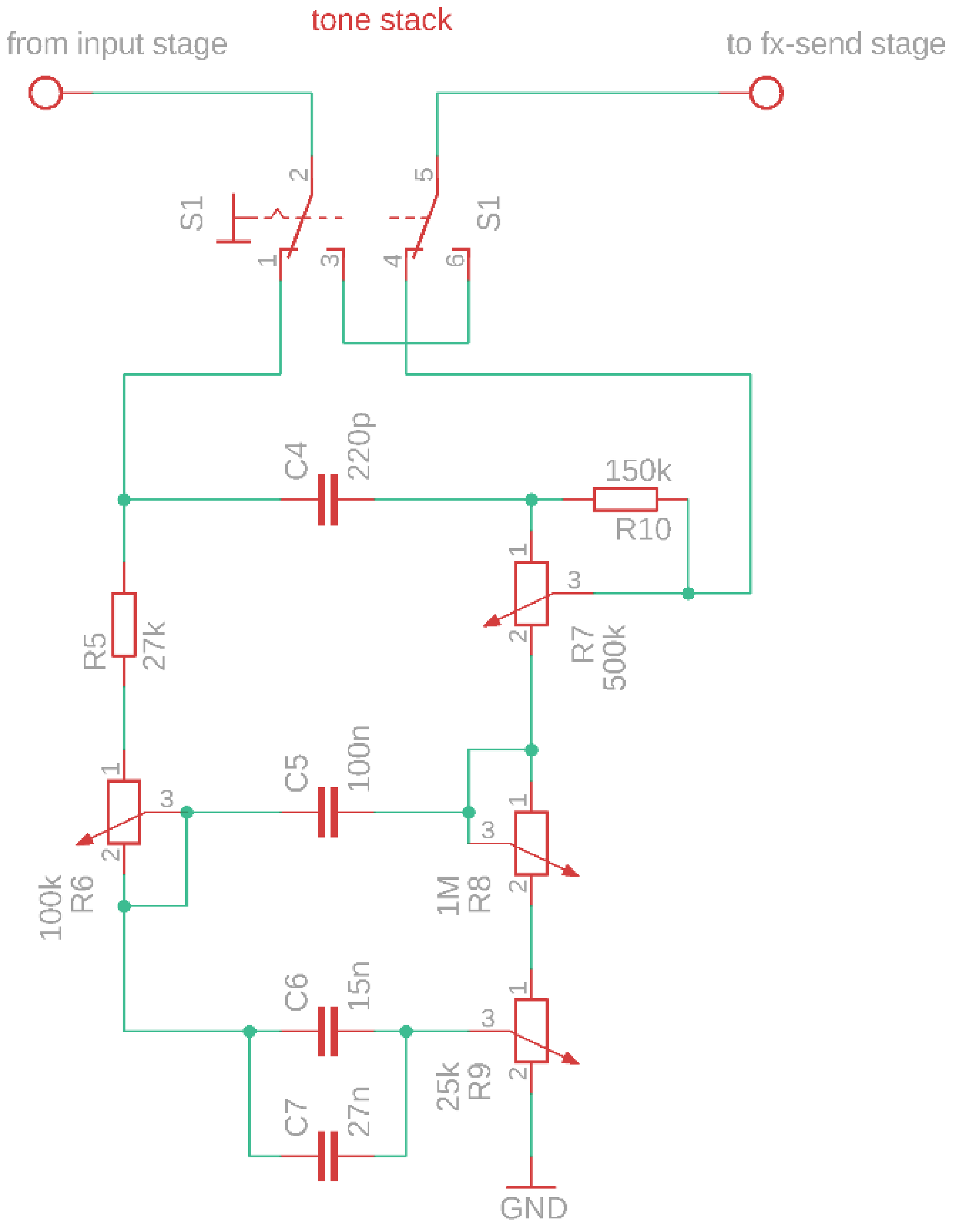


Figure 23: Schematic of the tone stack of the GNR-50[7].

Z_o can be determined by the following formula[2]:

$$Z_o = \frac{R_a \cdot r_a}{R_a + r_a}$$

R4 is the anode resistor of the previous stage and r_a is the anode resistance of this stage. The anode resistance is a constant of a valve and is given in the datasheet. For an ECC83, it is 62.5kohm. Those two resistances in parallel equal Z_o.

$$Z_o = \frac{R4 \cdot r_a}{R4 + r_a} = \frac{220k\Omega \cdot 62.5k\Omega}{282.5k\Omega} \approx 48.7k\Omega$$

As Z_o is large compared to the values of a normal Fender (figure 21: 38kΩ) or even a Marshall (figure 22: 1.3kΩ) the treble response is not as good as it could be, thus R10 was added.

Z_i equals, assuming the gain is turned fully up, R11 and R13 in parallel[2]:

$$Z_i = \frac{(1M\Omega)^2}{2M\Omega} = 500k\Omega$$

Comparing this value to the Fender and the Marshall it becomes apparent that it is a very common value.

Figures 24, 25 and 26 depict three frequency response curves for different settings of the voice knob when bass, middle and treble are set to their middle position. While the differences made by R6 may look subtle on the frequency response diagrams, they are very noticeable to the ear, as most affect the midrange the most, which is the most important frequency band of the guitar. The bass frequency band looks similar to the one of the Fender, mostly affecting very low frequencies below 100Hz, which is why it is a subtle control influencing more the character than the perceived volume of the bass frequencies

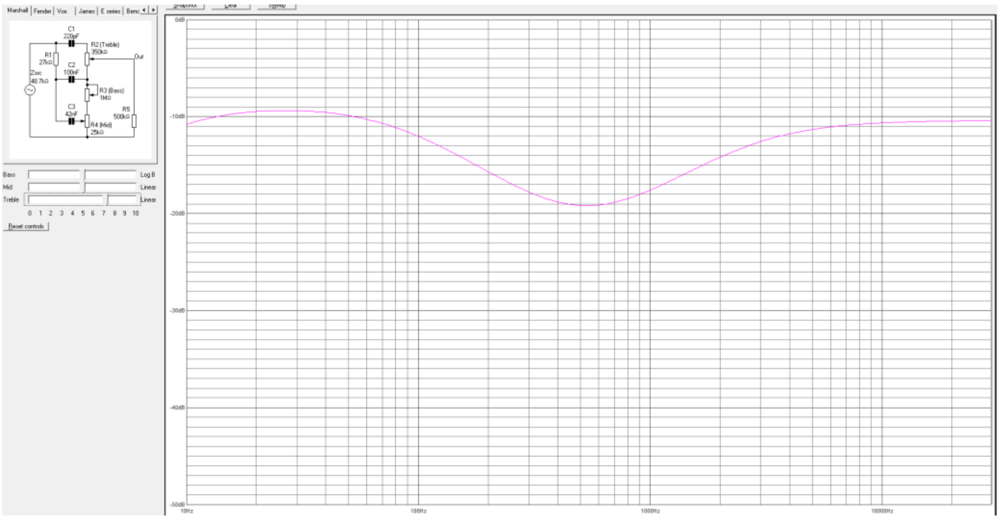


Figure 24: Frequency response of the tone stack of the GNR-50 with the voice control at its leftmost position. Bass, middle and treble are in their middle position[10].

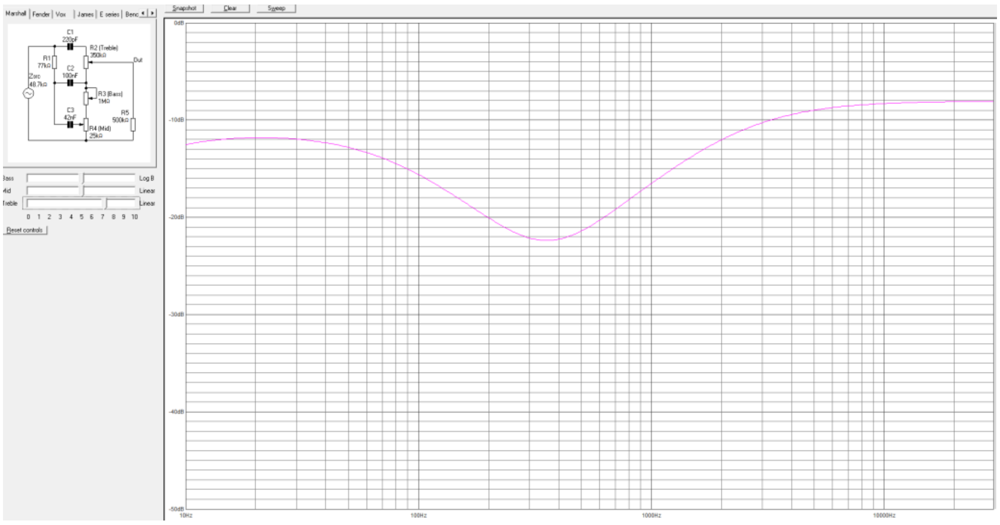


Figure 25: Frequency response of the tone stack of the GNR-50 with the voice control at its middle position. Bass, middle and treble are in their middle position[10].

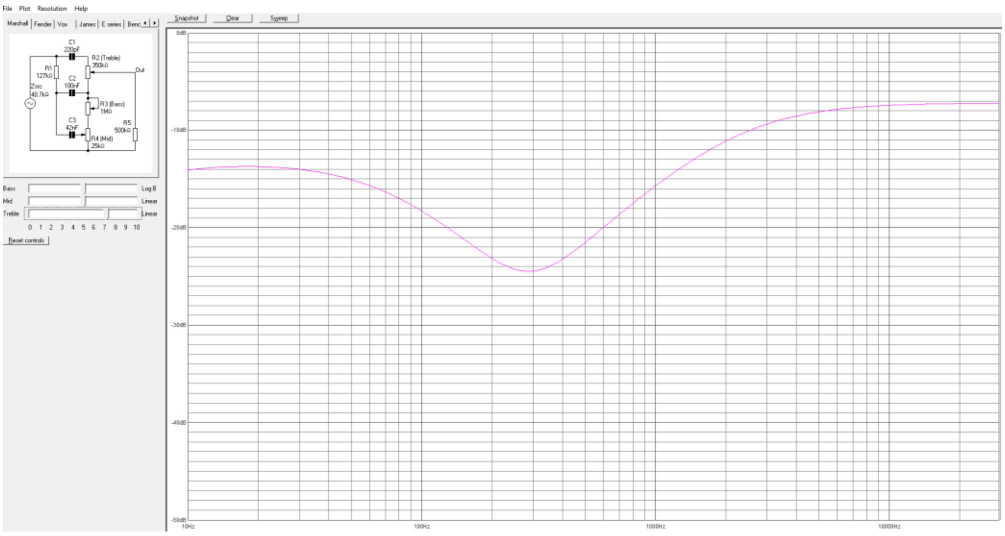


Figure 26: Frequency response of the tone stack of the GNR-50 with the voice control at its rightmost position. Bass, middle and treble are in their middle position[10].

Fx-send stage

The fx-loop is one of the core features of the GNR-50 as it is a very useful function. The schematic of this stage is shown in figure 27. The input signal gets first attenuated by the gain potentiometer R11. C8 and R12 form a circuit called treble bleed, which lowers the impedance between connection 1 and 2 for high frequencies. Therefore, the gain control affects more low- and midrange frequencies than treble. This is very useful as it allows to further shape the tone when playing clean. When playing distorted and the tone stack is bypassed, the treble bleed ensures that also lower gain settings sound nice and clear.

The gain stage is basically a cathode biased common cathode gain stage. However, since the level of the fx-loop is the same as guitar level the output signal is picked up at the cathode. This is also why this stage cannot have a bypass capacitor, as this would eliminate negative feedback and therefore the output signal.

R18 is an internal potentiometer to adjust the volume of the fx-send. The output impedance is in any case lower than 5kohm, which is necessary to avoid noise and signal degradation. If no cable is connected to the fx-loop, the signal gets directly passed to the fx-return stage.

Figure 28 shows the load line drawn of V2. The load equals the sum of the anode resistor R16 and the cathode resistor R17. An input signal of 1Vpp would lead to an anode current signal of 1mApp. As this signal passes through R17, it will result in a voltage signal of 1.5Vpp. Therefore, the gain at the cathode is 1.5. However, this calculation does not include the negative feedback of R17 and the loading effect of R18, thus the actual gain is smaller than the calculated value.

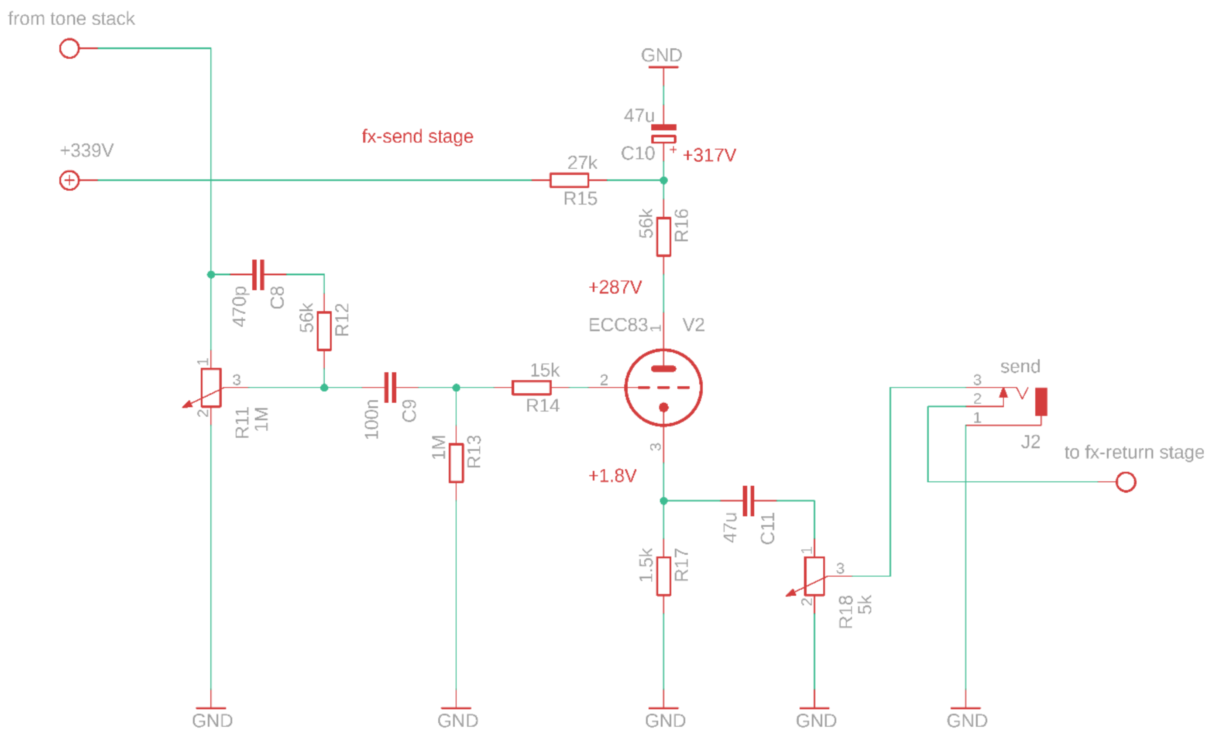


Figure 27: Schematic of the fx-send stage[7].

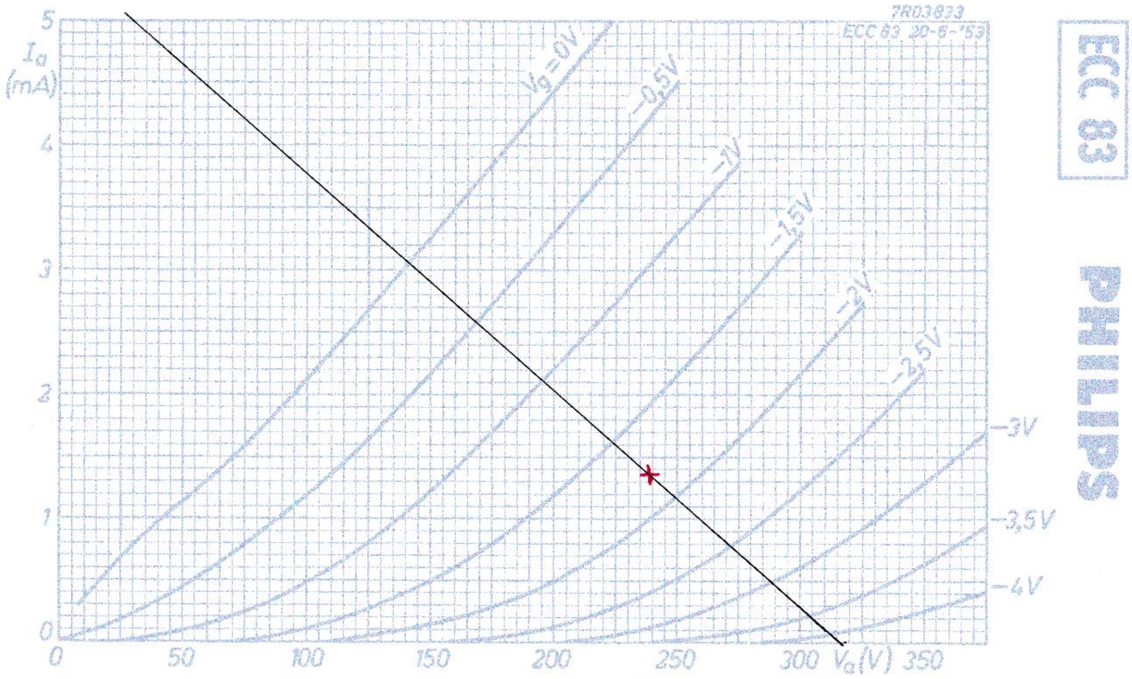


Figure 28: The load line (black) and the bias point (red) of the valve of the fx-send stage V2[4].

Fx-return stage

The great thing about a serial fx-loop like the one of the GNR-50 is that the power amp also can be used independently. There are effect pedals which sound similar to the preamps of famous amplifier. Those can be plugged straight into the fx-return and therefore combine the sound of the pedal with the 50 watt output power and EL34 sound of the GNR-50's power amp.

The fx-return stage is at its heart the same as the input stage. Its schematic can be seen in figure 29. Again, small guitar level signals have to be amplified with maximal gain, so it is not special that the two stages are very similar. The most important parameters: bias as well as anode resistor are identical. The gain of this stage is again 75 without any additional loading. Figure 30 shows the load line.

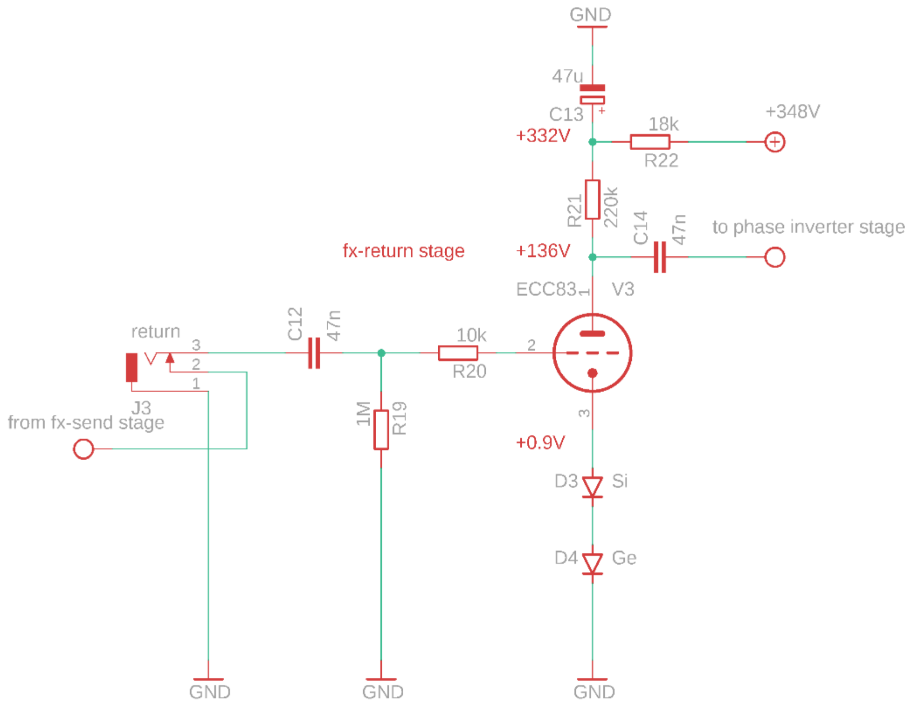


Figure 29: Schematic of the fx-return stage[7].

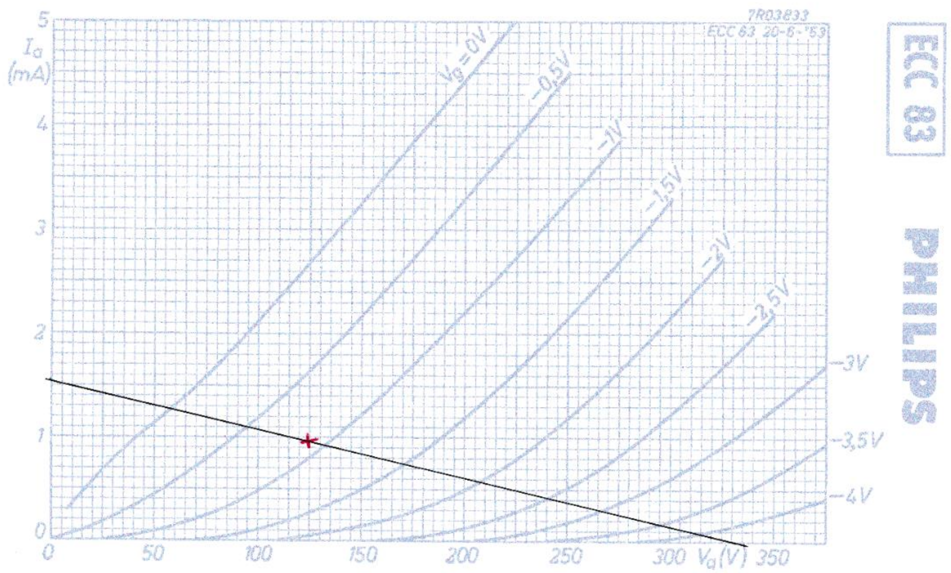


Figure 30: The load line (black) and the bias point (red) of the valve of the fx-return stage V3[4].

Phase inverter stage

Since the power valves run in a push-pull configuration they need to receive phase inverted signals. To accomplish this, a so-called cathodyne phase inverter was used in this amplifier. Its schematic can be seen in figure 31.

The cathodyne works according to the following principle. Both voltages across R26 and R28 will be the same at every point in time since the same current I_a flows through them and they have the same resistance. However, the AC voltage signals sent to the power stage will be phase inverted, since they are taken on the opposite sites of their resistor.

While this principle is easily understandable the actual analysis is more complex. The cathodyne in the GNR-50 is cathode biased. R27 and R28 form a voltage divider thus the point between them is at the voltage:

$$\frac{67V \cdot 1.5k\Omega}{57.5k\Omega} \approx 65.3V$$

The grid is connected to this point, meaning the bias is:

$$65.3V - 67V = -1.7V$$

To make it easier, R27 will ignored from now on, as we now know the bias. Including R27 in the rest of the analysis would make it much more complicated, since it unequally loads the cathodyne. For the cathodyne phase inverter, a so-called differential load line can be drawn. The differential load line describes the voltage between the two outputs. The load is the sum of R26 and R28[2].

$$56k\Omega + 56k\Omega = 112k\Omega$$

The differential load line can be seen in figure 32. As usual this is the load line without the effect of loading from the next stage taken into consideration. However, since the load from the power stage is always the same and given by R32 and R36, it can be easily drawn this time. The new load equals the sum of R26 in parallel with R32 and R28 in parallel with R36[2].

$$\frac{56k\Omega * 100k\Omega}{156k\Omega} + \frac{56k\Omega * 100k\Omega}{156k\Omega} \approx 72k\Omega$$

As R32 and R36 are only 100KΩm the loading effect is large, and this leads to noticeable rotation of the load line around the bias point. Since the cathodyne operates with over fifty percent negative feedback due to R27 and 28, the gain cannot be read from the load line anymore. The gain for each output of the cathodyne is always somewhat less than one. There can be a formula derived to calculate exact gain, but for a guitar amplifier, it is a good approximation to assume the gain just to be one[2]. The same applies for the unequal load created by R27, it is not perfect in theory but works and sounds good and therefore serves its purpose.

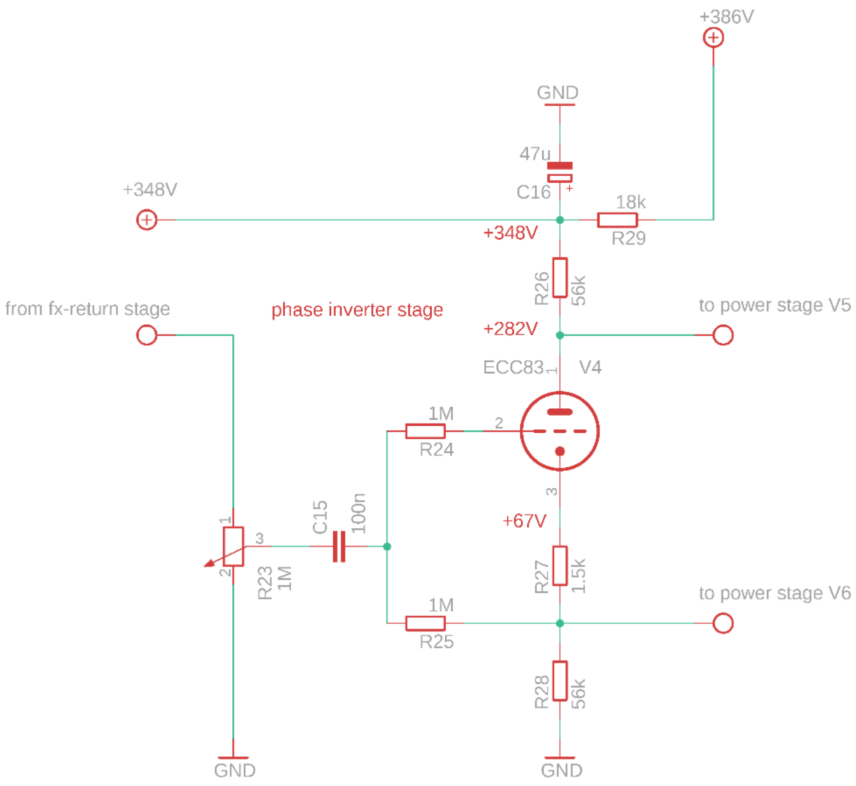


Figure 31: Schematic of the phase inverter[7].

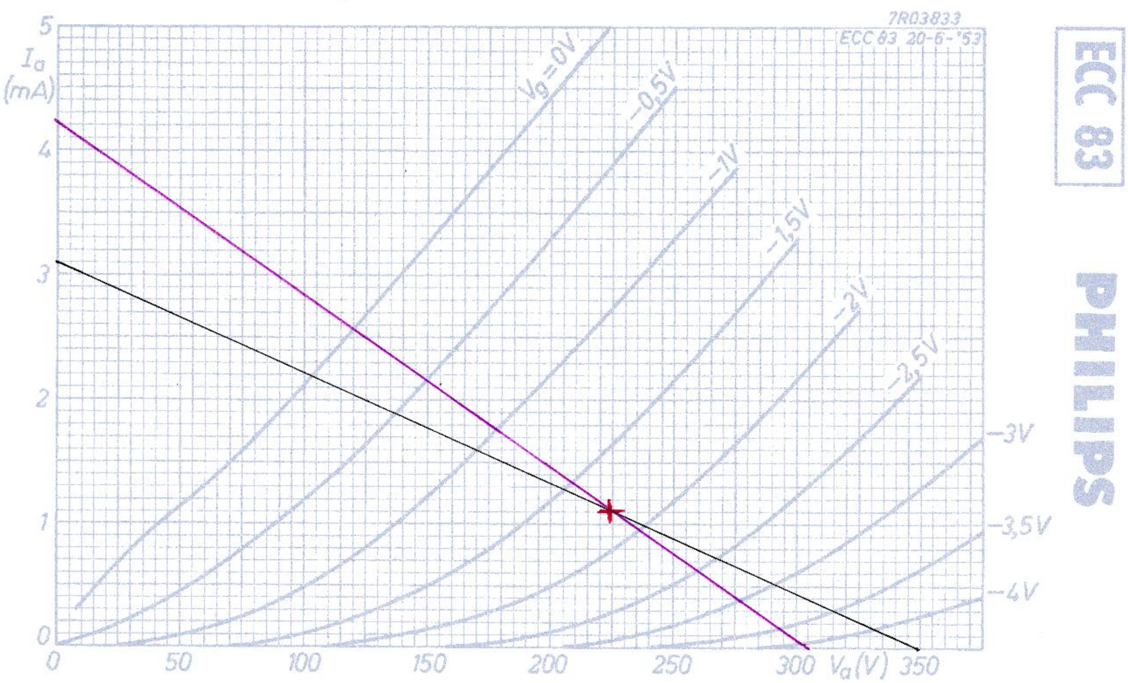


Figure 32: The load line without loading (black) and bias point (red) of the valve of the phase inverter stage V4. When loading from the power stage is taken into consideration, the load line (purple) noticeably rotates around the bias point[4].

Power stage

The two cathode biased EL34s run in a class AB push-pull configuration. As can be gathered from figure 33, the anodes of V5 and of V6 are both connected to the outer ends of the primary winding of the output transformer TR1. The HT^+ of +386V is connected to the middle of the primary. While not amplifying any signal, currents of equal magnitude flow through V5 and V6. The magnetizing effect of the currents on the transformer's core cancels because they are equal in magnitude but opposite in direction. It has already been mentioned before that the input signals for both valves are phase inverted, therefore V5 will have a positive peak of the input signal, which lets V5 conduct more current, while the input signal of V6 will be at its negative peak, making it conduct less current and vice versa. The effective current through the primary is thus no longer zero, but changes with the input signal and flows in the direction of the valve which is currently receiving the positive half of the signal. This AC current through the primary will lead to changing magnetization of the transformer's core, which induces an AC Voltage on the secondary, driving the speaker. The configuration is called push-pull because one valve pushes (conducts less) while the other pulls (conducts more).

The Switch S2 allows to select either the 8Ω or 16Ω tap of the secondary to match the impedance of the used speaker. The output transformer also offers a 4Ω tap, but it is not used in the circuit, since 4Ω speakers are rather uncommon. The impedance on the primary for an 8Ω load connected to the 8Ω tap of the secondary equals 3.2kΩ. Thus, the impedance scaling factor of TR1 is 400.

The class of the amplifier tells how long each of the valves is conducting during one period of the input signal. In a class A amplifier, both valves are conducting throughout the whole period of the signal. This is how an ideal amplifier should work, but it is not always practical, since class A operation is very inefficient. To be able to conduct throughout the whole period of the input signal, the power valves need to be biased like small signal valves, so that they can accurately follow the input signal. This has the consequence that the power stage has a lot of anode current even when there is only a small or no signal at all amplified and thus has a large power consumption, which makes it inefficient.

Class B is a much more efficient operation mode. Both valves are biased at cut-off and each of them only conducts throughout one half of the period of the input signals period. Thus, in class B, the power consumption is much more dependent on the output volume. Without an input signal, both valves are in cut-off and do not conduct any anode current, which makes Class B very efficient. However, class B is not suited for audio amplification, since it leads to audible crossover distortion, which happens when the transition between the positive half and the negative half of the output signal is distorted. On an oscilloscope, this looks like the very middle part of the wave has been cut out and the top and bottom have been put back together.

Class AB is a hybrid of class A and class B combining both their benefits to some extent. In class AB operation, the valves are biased colder than in class A and conduct less current while in idle. For small input signals both valves are able to follow them and the amplifier operates in class A. For signals with greater amplitudes, each of the valves reaches cut-off during the negative peak of their input signal and thus the amplifier switches to class B operation. Although a class AB amp does not operate as linearly as a Class A, if designed and biased correctly, there is no unpleasant distortion audible, like in a class B amplifier, yet it is still more efficient than a class A amplifier.

The power valves are cathode biased through the common bias resistor R34. The bypass capacitor C18 eliminates negative feedback of all frequencies of the audio spectrum. Often, power valves are biased in fixed bias, but because they are operating near their limiting values, the bias needs to be readjusted with every exchange of the valves to match the deviations between the new and the old pair of valves.

As the cathode bias changes with the idle current, it adjusts itself to some extent to the currently used valves and therefore allows to switch valves without any adjustments.

The load line of a class AB amplifier is more complicated than the one of a single small signal valve, since the load for the valves is different when operating in class A while when operating in class B. While both valves are conducting the load for each one equals half of the whole load of the primary 3.2kΩ, therefore 1.6kΩ. When the amplifier enters class B, one half of the primary is not part of the circuit anymore and therefore the voltage ratio halves and the impedance ratio quarters. Thus, the load is now 800Ω[11].

There are two further things which have to be taken into consideration. The bias voltage across R34 makes a considerable part of the HT^+. Therefore, it is important in this case not to forget that the maximal V_a is not the same as HT^+, but the HT^+ minus the bias voltage. Also, the DC resistance of the transformer is very small since it is just the resistance of the wire of the primary winding. Therefore, it is common to assume that the V_a at the bias point is the same as the maximum V_a. As we can read from the measured values, this is not entirely true as V_a is 2V less than the maximal V_a, but it is nonetheless a good approximation[11].

The real load line can be constructed by drawing both load lines for the load of class A and class B with their corresponding load and the maximal V_a and then parallel shifting the class A load line up until it crosses the bias point. The point where the shifted class A load line now crosses the class B load line is where the other valve reaches cut-off and the amplifier enters class B. The load line drawn for the GNR-50 can be seen in figure 34. Luckily, the screen grid voltage of +357V is very close to the +360V which the datasheet had a plate characteristic drawn for, meaning it is possible to use this diagram and it is not required the draw them by hand[11].

Choosing the correct bias point is much more critical for power valves than for preamp valves. A bias point which is chosen too low can make the amplifier sound bad and thin or even lead to crossover distortion like in a class B amp. But the bias can also not be biased as high as one would like, since the valves have a maximal anode dissipation. While preamp valves are commonly far away from this limit, it is common for power valves to operate near their maximal dissipation. The maximal anode dissipation for an EL34 is specified at 25W. This can be seen marked in the plate characteristics by the rounded curve labelled W_a. The load line crosses this line, which means during amplification, the dissipation rises above the specified maximum. This is, however, not bad, since the amplifier runs in class AB. This means that the valves will also be in cut off for a considerable part of the amplification process, therefore the average anode dissipation is below the allowed maximum. The rule of thumb is that anode dissipation at the bias point should be somewhere between 70% and 85% of the maximum anode dissipation[11].

To determine the maximal output power of the power stage, the point where the maximal possible power is delivered to the load has to be found. It is where the load line crosses the grid curve for $V_g = 0V$.
At this point, there is the most possible amount of current flowing through the load as well as the largest possible voltage across it. To arrive at the rms power, one has simply to multiply the rms current with the rms voltage, which can be found by dividing the respective amplitude by the square root of two.

$$P_{rms} = I_{rms} \cdot V_{rms} = \frac{I_{max}}{\sqrt{2}} \cdot \frac{V_{max}}{\sqrt{2}} = \frac{I_{max} \cdot V_{max}}{2}$$

Solving this equation for the power stage of the GNR-50 leads to

$$P_{rms} = \frac{I_{max} \cdot V_{max}}{2} = \frac{370mA \cdot (357V - 65V)}{2} \approx 54W$$

This value can be realistically rounded to 50 watts rms. Comparing this value to other amplifiers shows that this power is reasonable. There are many amplifiers with two EL34s which are rated at 50 watts such as the Marshall Origins 50 and the Orange Rockerverb 50.

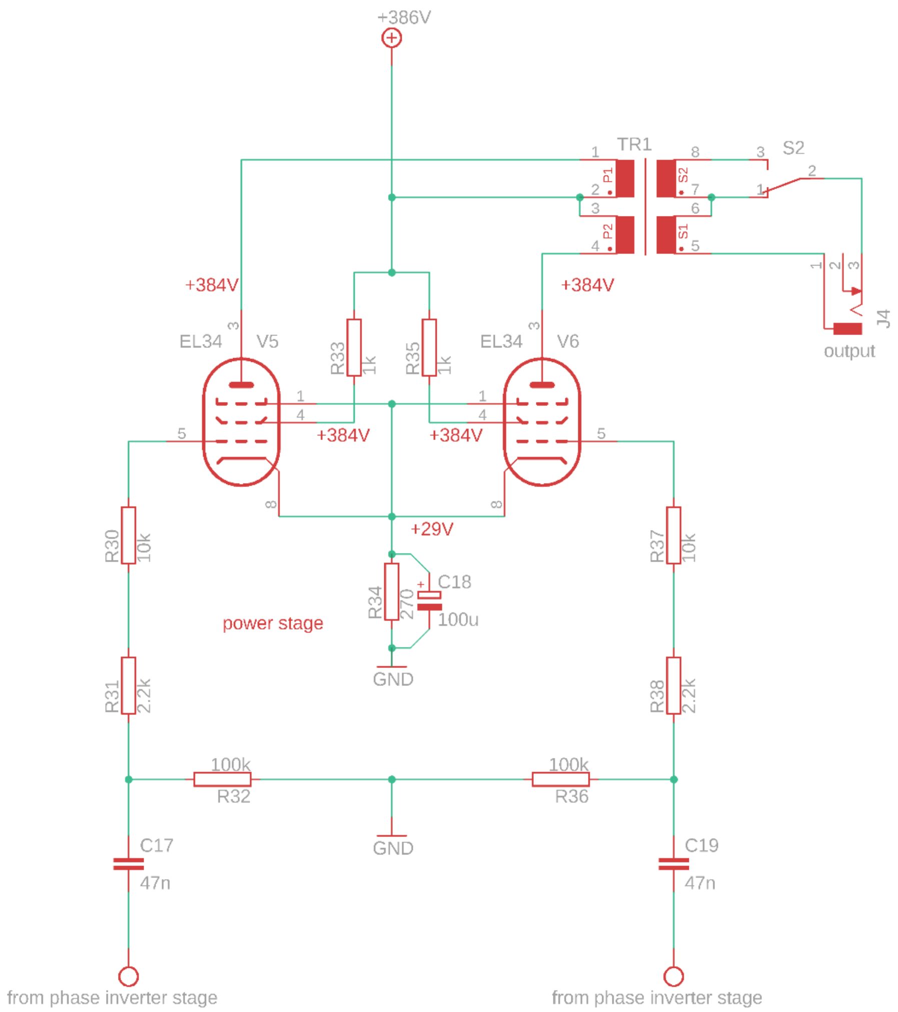


Figure 33: Schematic of the power stage[7].

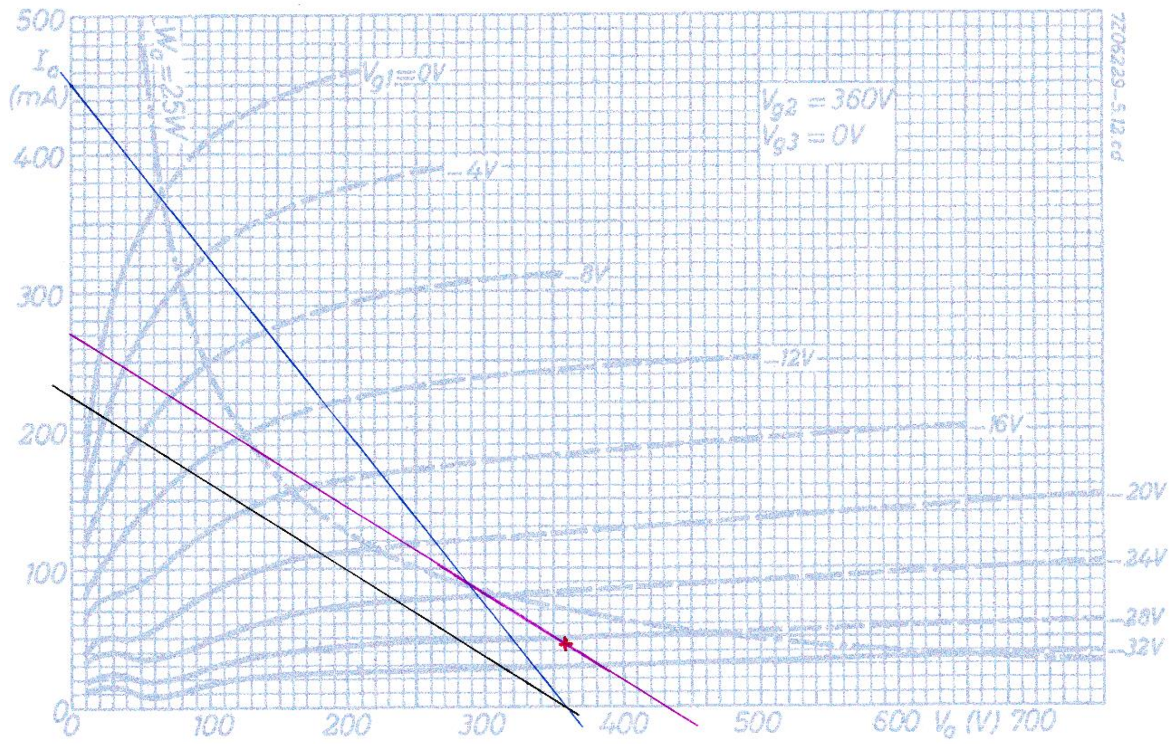


Figure 34: The class A load line (black), class B load line (blue), shifted class a load line (purple) and the bias point (red) of the power valves V5 and V6[5].

Distortion Stage

Although it did not end up in the finished amplifier, the schematic of the planned distortion stage is shown in figure 35, since it was designed with some nice features in mind. The distortion stage conists of common cathode gain stages with very common values for the anode resistor and grid stopper. R1 is a potentiometer to set the input level of the stage and therefore the amount of distortion. R6 and R10 are trim potentiometers, which were internally set to adjust the amount of distortion from V2 and the output volume so that the stage is not too loud when engaged.

What makes this stage somewhat special are the switches S11 and S2. S1 is a three-way toggle switch and adds either C2, C4 or none of them in parallel with R3. This results in either a boost of the higher frequencies, a full range boost or no boost at all by controlling the negative feedback. S2 switches between D1 and D2. which is either a really cold bias of -2.7V by the green LED or a really hot bias of -0.7V by a normal silicon diode. The different bias would lead to different amounts of grid current and cut-off clipping and therefore change the sound of the distortion. Originally, the amplifier was intended to have one distortion stage before the tone stack and one after it. Both of them were supposed to be turned on and off to either use them independently or together. Unfortunately, the space in the case ran out during the project so they had to be left out and distortion is now only produced by the fx send stage.

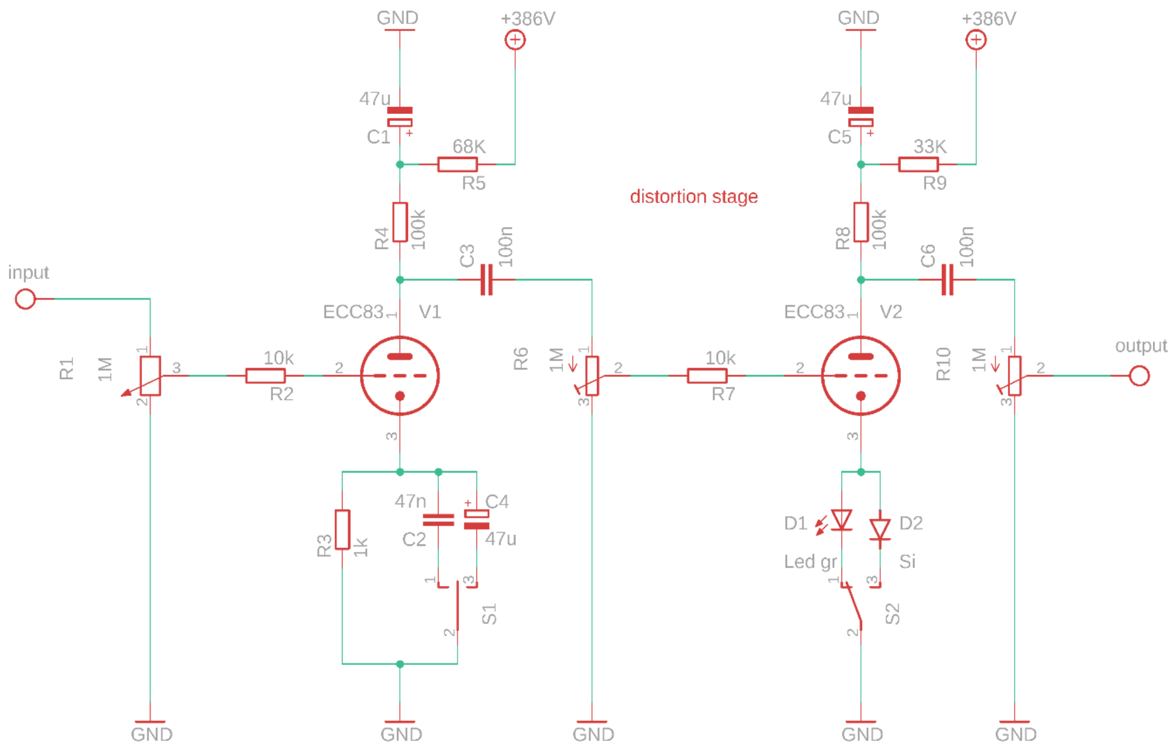


Figure 35: Schematic of the distortion stage[7].

3.3 Building Process

Before the construction of the amplifier could begin, there were some preparations to be done. The time between May and July was spent studying the theory of valves and their application in guitar amplifiers. Many thoughts were spent on what the amplifier should be in the end. How many and which features it should have. At first, the amplifier was planned to have only one power valve, since this would not require a phase inverter stage and the construction of the power amp would be overall much simpler. A so-called single-ended amplifier would have naturally less power than one with two valves in push-pull, but it should still be by far enough for using it at home. However, this idea was discarded while selecting the transformers. Single-ended amplifiers need special output transformers, since the net current through the transformer during idle is not zero, like in a push-pull power amp. These transformers are more expensive, therefore less popular for manufacturers and thus not as widely available as push-pull output transformers. Both power and output transformers were replacement parts for Marshall amplifiers[12].

In August the actual building process began. Since the valve sockets were supposed to be connected by wires to the rest of the circuit and not directly soldered onto the boards, as this is a less durable construction method, the casing of the amplifier was the first thing which had to be crafted. The casing follows the design of many valve amplifiers, where the valves and transformers are on the same plane with the rest of the circuitry beneath them.

The next thing which had to be done was to build the power supply. Although the final construction of the power supply is very simple, it was a challenging process, since the high voltages also require special capacitors built to withstand those voltages. The problem was that the secondary winding, which was rated at 300VAC, was actually delivering 330VAC and which would result when rectified in 459VDC. Normal capacitors are only available up to 450VDC and only super capacitors are rated for higher voltages. Super capacitors are expensive but also physically very large, so it was not possible to use super capacitors for all filter capacitors and it was unclear at that time how safe it would be to run 450VDC capacitors at 459VDC. For the reservoir capacitor, a super capacitor rated for 500VDC was used, and in the end 450VDC capacitors were used for the filtering[13]. This was no problem, because as soon as the load on the transformer increased with connection of the power valves, the voltage dropped considerably to a level even lower than specified.

When it came to the construction of the actual amplifier circuit, it was the power amplifier which was built first, since it is able to amplify the guitar signal enough to drive a guitar speaker. Even without any equalizing or distortion, sound would at least be audible and indicate if everything worked as it should or not. The design and construction of the power amplifier was, although challenging not connected with many technical problems. The very first version of the power amp did oscillate, but this was easily fixed with bigger grid stoppers at the power valves. Another problem was that the amplifier distorted at rather low volumes, which was a problem of the bias of the phase inverter and could also be solved with ease. Throughout the project, there were some other minor modifications made to the power amplifier to improve its sound and output power.

A problem which started to get noticeable was that working with the case was not as easy as first estimated. Since all valve sockets had to be connected to the circuit boards with wires, the result was a big jungle of different coloured wires. Long wires would be good, since this makes the modification of the circuit boards easier, but longer cables also can lead to more mess and pick up much noise from the environment and the amplifier's power supply. The wiring on the amplifier was redone multiple times, which was way more time consuming than anticipated. The solution which was used in the end included longer leads of three wires in one shielded cable. Therefore, every triode could have its own shielded cable, which should ensure silent operation.

While working on the preamp, the next problem occurred. After all the shielded wires were soldered to the valve sockets, it became obvious that there will not be enough place for the whole planned preamp. While the shielded cables were useful in theory and less chaotic than single wires for every pin of the sockets, they were really stiff and inflexible because of their thickness, which caused them to use up more space, making the circuitry of the amplifier even harder to reach. This required a change of plans. The preamp was considerably reduced in size. Two independent distortion stages and additional buffer stages for the tone stack were omitted, leaving the preamp how it is now.

The amplifier was then basically finished, only a few more component changes were done to further improve its sound quality and versatility. Theoretically, there is much potential to further modify the amplifier's circuit, however, due to the mentioned wiring and space issues part replacements are not easily done as many of the parts hard to access.

Pictures of the building process are found in the appendix.

4. Measurements

To further understand valves some experiments and measurements were conducted. Overall there were eleven ECC83s available for the test. Some of them were from the same brand whilst others were from other brands. Further information on the eleven test valves, the measured data in table format and pictures of the experimental setup can be found in the appendix.

4.1 The Test Circuit

The different tests on the ECC83s were done with a discrete test circuit. Its schematic can be seen in figure 36. It is kept as simple as possible to ensure easy measurements and analysis. The HT^+ is taken from the reservoir capacitor of the amplifier and is therefore 386 volts. The heater filament of the tested valve was powered by the 6.3VAC secondary of the amplifier's mains transformer. Trim potentiometer R1 acts as a variable anode resistor and R2 as a shunt resistor to determine the current through the triode by measuring the voltage across it. S1 changes between the two triodes in the same valve. The cathodes are directly connected to ground. The bias is provided by a fixed bias circuit. An external 9 volts supply is connected with its positive terminal to ground, thus supplying negative voltage. R5 acts as a voltage divider to select the bias. C1 and C2 are coupling capacitors. R3 and R4 form a voltage divider to attenuate the signal to a level which is safe for the oscilloscope.

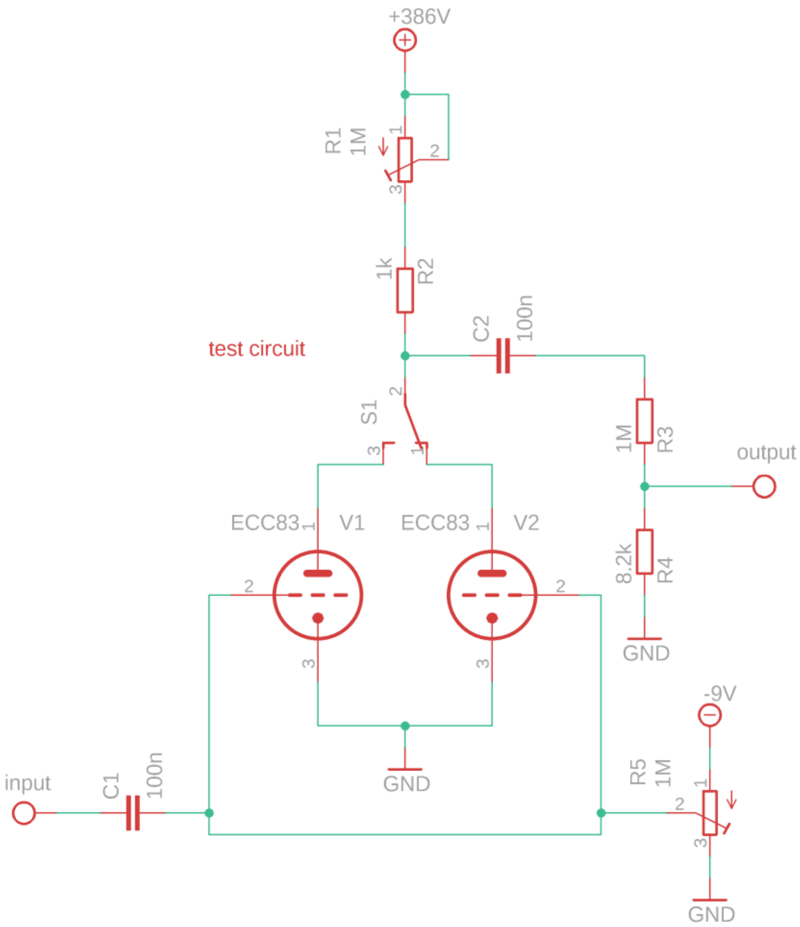


Figure 36: Schematic of the test circuit[7].

4.2 Measuring the Plate Characteristics

Maybe the most important information about a certain valve is its plate characteristics. They are normally specified in the data sheet, but, like every other electrical component, triodes are not perfectly consistent. To compare the actual plate characteristics of both triodes of V1 to the ones specified in the data sheet, multiple measurements under static conditions were taken.

Procedure

For this experiment, three multi meters were used. One measured the bias voltage, the other the voltage across the shunt resistor and the last one the voltage across the trimmer and the shunt. This voltage subtracted from the HT^+ equals V_a. The multi meter was not connected to the triode in parallel, since this would lead to less accurate results, since the multi meter would always conduct some current and lead to a voltage divider together with the anode and shunt resistor. Connected like done in the experiment does still affect the circuit, but now it is the anode resistor which is influenced and not the triode. Since the anode resistor is a trim potentiometer, this does not matter. First the bias trimmer was adjusted to the desired value, then the anode voltage was set with the anode trimmer. The anode current could then be calculated with the voltage across the shunt resistor and its resistance by applying Ohm's law.

The triodes were tested at the same bias voltages as specified in the datasheet. A measurement was taken for every 25 volts of anode voltage.

Results

Comparing the measured values to the datasheet from the manufacturer in figures 37 and 38 shows, that, whilst the shape of the grid curves looks similar, there are big deviations concerning the exact values. For example, for a bias of 0 V and an anode voltage of 200 V, the datasheet states an anode current of around 4.4 mA, while triode A measured 4 mA (-9%) and triode B measured 5 mA (+14%).

It is easy to see that for every combination of bias voltage and anode current, triode B has considerably higher anode current. In a circuit where the bias is set by the voltage drop of the anode current through a cathode resistor, triode B would therefore be biased colder than Triode A.

As triode B had overall a higher anode current, it was possible to measure some points at lower voltages which were not possible with triode A. This is because the anode voltage is the result from HT^+ of 386 V minus the anode current times the anode resistor which, has a maximum of about 1MΩ in this test circuit.

Discussion

There can be some deviations in the plate characteristics from triode to triode; even between the two triodes within the same valve. This not only affects anode current, but also the gain of the triode in a circuit as with increasing distance of the grid voltage curves, the gain also increases. However, this effect could be reduced by using a cathode resistor without bypass capacitor to bias the triode, as it will introduce negative feedback and therefore will decrease the difference between triodes with higher and lower gain.

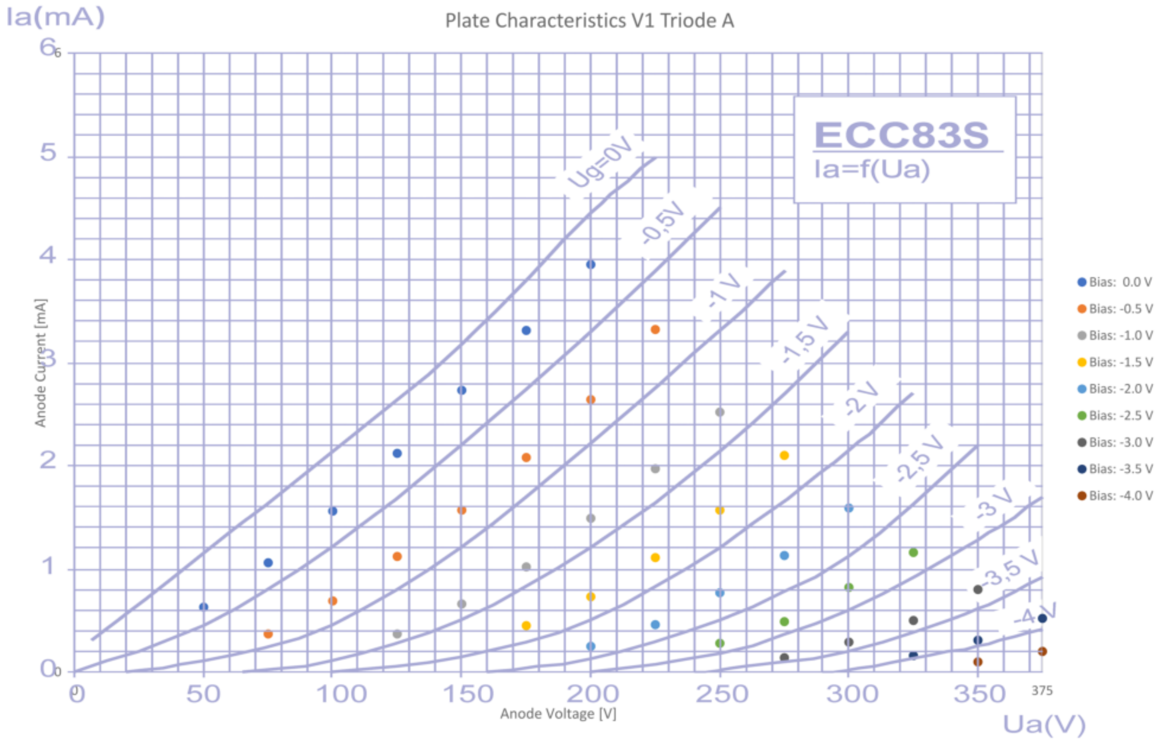


Figure 37: Measured plate characteristics (coloured dots) compared to the plate characteristics given by the manufacturer (pale blue lines) of triode A of V1[14].

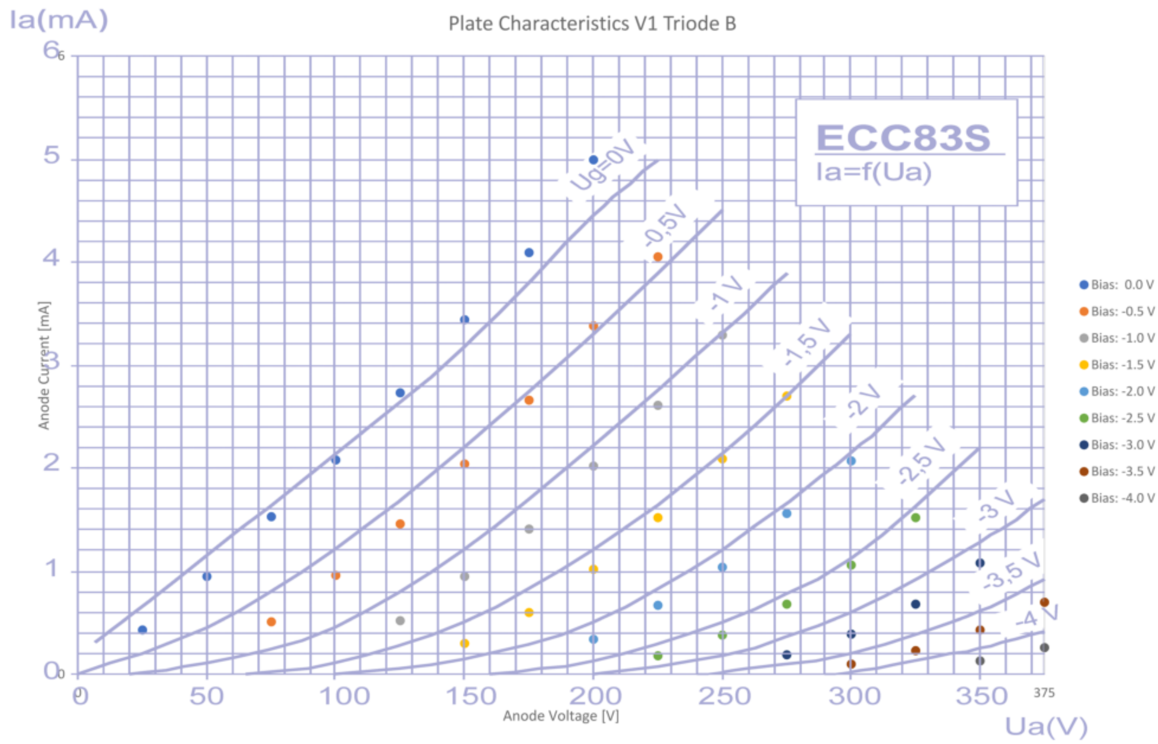


Figure 38: Measured plate characteristics (coloured dots) compared to the plate characteristics given by the manufacturer (pale blue lines) of triode B of V1[14].

4.3 Load Resistor Measurements

The plate characteristics diagram indicates that a bigger load resistor and therefore a less steep load line will lead to greater amplification. To verify this theoretical assumption, dynamic measurements with different anode resistors were taken.

Procedure

For these measurements, the bias was set to a reasonable voltage of -1.5 V, as it would be used in a normal gain stage. The Input signal was a 1.0 kHz sine wave 2 volts peak-to-peak (Vpp) supplied by a signal generator. Both triodes of V1 were tested again with anode resistors of 50, 100, 200 and 400 kΩ.

Results

Figure 39 shows that with an increasing anode resistor, the gain does indeed increase. It is also noticeable that the gain of triode B is overall greater than the one of triode A, which can be explained by the different plate characteristics as observed and discussed before.

Discussion

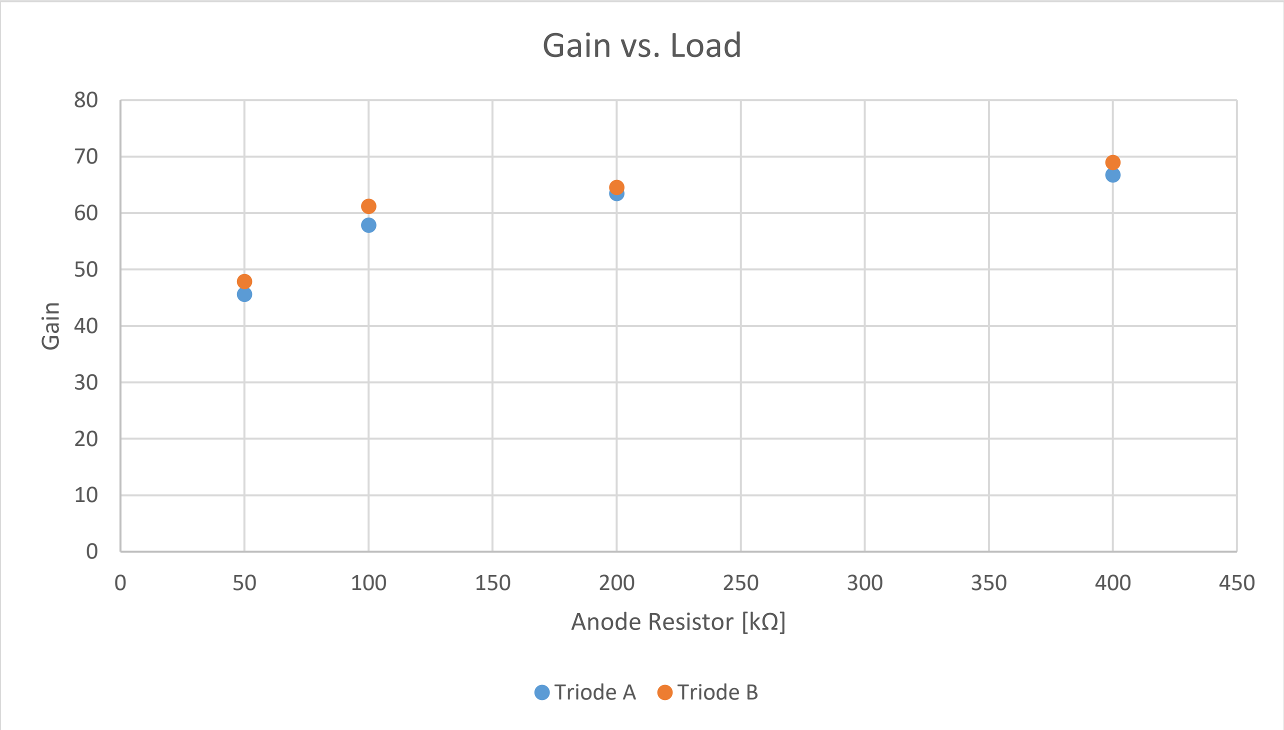


Figure 39: Gain increase with load resistor.

While the gain does, as assumed, increase with a larger anode resistor, this increase is not linear, but a curve with a horizontal asymptote. This can be explained by the fact that every triode has a theoretical maximal gain which would be achieved by a horizontal load line caused by an infinitely big anode resistor. The diagrams of the measurements show that doubling the anode resistor from 50 to 100 kΩ yields a much higher increase in gain than doubling it from 100 to 200 kΩ.

4.5 Bias Measurements

To observe the changes in gain with the bias the two triodes of V1 were tested at different bias voltages.

Procedure

The anode resistor was set to a typical value of 100 kΩ and the input signal was again the 1.0 kHz sine wave 2 Vpp in order to avoid clipping unless extreme bias values were chosen.

Results

Figure 40 shows the output signal compared to the bias. The comparison is not done with respect to gain as before, since the term gain is somewhat misleading when talking about distorted and clipped signals. The attenuation of the voltage divider explains the small values.

Bias voltages above -1V (figure 41) as well as below -3V (figure 42) resulted in noticeable distortion. While for a bias below -3V normal cut off clipping occurred, there was no grid current clipping for a bias above -1V. This is because there is no grid stopper in the test circuit and the output impedance of the oscilloscope is very low. Proof for this is that the signal measured at the grid is not distorted, which it should be if grid-current clipping occurs. Thus, the distortion seen in figure 41 is actually caused by the nonlinearities of the valve at a V_g over 0 Volts. Between -1 V and -3 V, the gain decreases with a colder bias, which is caused by the difference in distance between the grid voltage curves in the plate characteristics. Yet again, the output signal of triode B was larger than the one of triode A at the same bias voltages.

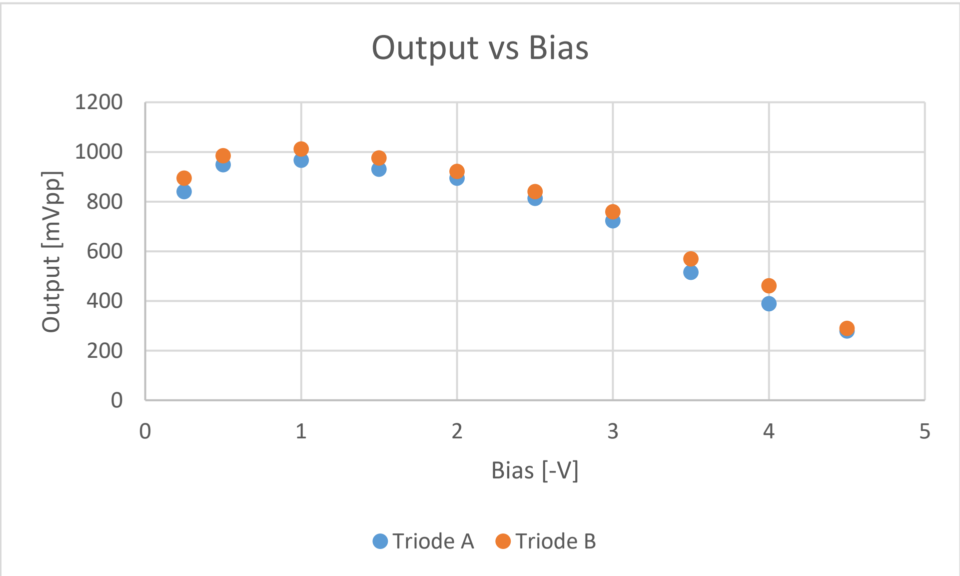


Figure 40: Output changing the bias.

Conclusion

The chosen bias voltage affects the way the triode operates in multiple ways. Therefore, the bias voltage can be chosen to best suit the application of the gain stage. For most headroom, the bias should be set at around -2 V. If the gain stage only receives very small signals, the triode can be biased warmer to increase gain. If the gain stage is meant to be overdriven, the bias point determines whether grid current clipping or cut off clipping is first achieved. Interesting additional measurements would have been to include different sized grid stoppers to observe the grid current clipping.

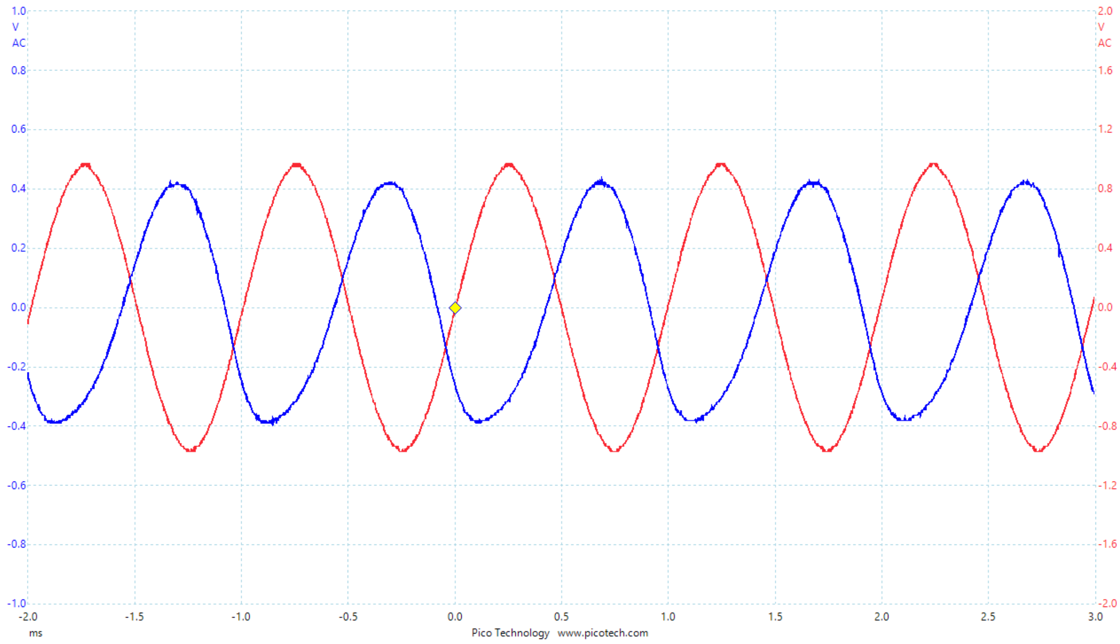


Figure 41: Valve 1 Triode A at a bias of -0.25V. The negative peaks of the output signal (blue) are distorted due to the nonlinearities of the valve. Since the input signal (red) is not distorted, this cannot be grid current clipping[15].

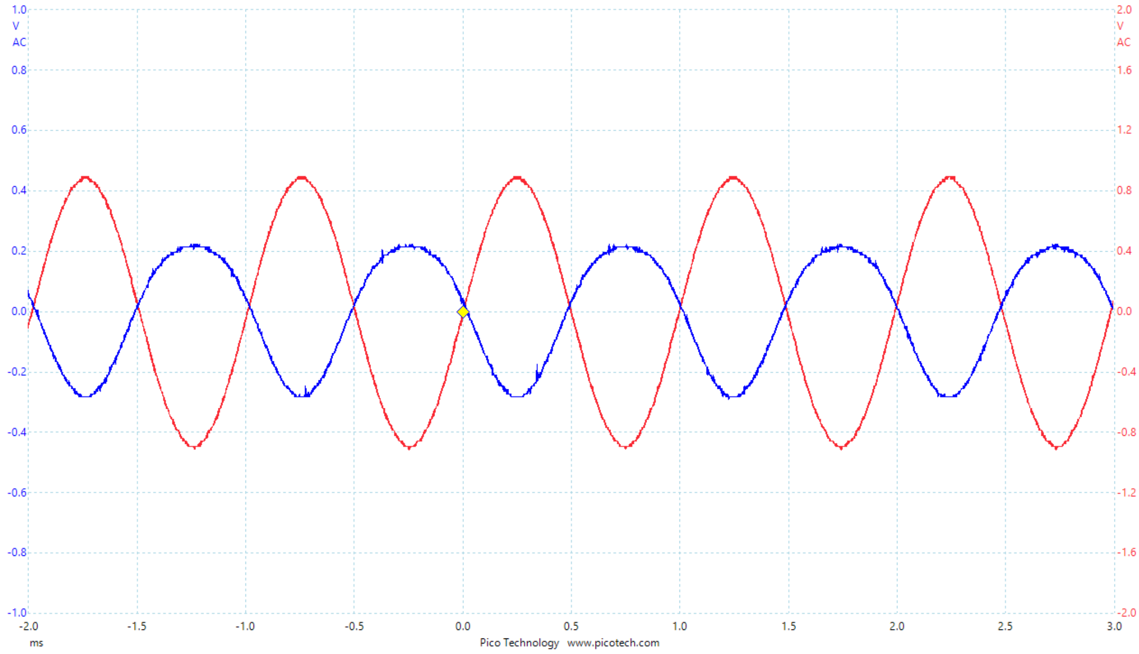


Figure 42: Valve 1 Triode A at a bias of -3.5. The positive peaks of the output signal (blue) is distorted by cut-off clipping. Although clipped, the peaks look still very rounded, which is typical for the clipping caused by valves[15].

4.6 Volume Measurements

The Micro Dark, made by Orange Amplifiers, is a so-called hybrid amp. The output section is pure transistor technology, whereas the preamp is a mix of op-amps and a single ECC83 to create the distortion. Because this amplifier uses only a single valve, it seemed like it would be ideal to test different brands of ECC83s in it to see whether they differ in sound. While playing the amplifier with different ECC83s in it, the perceived differences were extremely large. Not only did the valves differ in their frequency response, but there were also huge changes in volume.

To further investigate the inconsistencies between the single valves, all 11 available ECC83s were tested under the same conditions in the test circuit.

Procedure

The triodes were biased at -1.5 V with an anode resistor of 100 kΩ. The input signal was 1 kHz at 5.5 Vpp to overdrive the triode. This was done because the Micro Dark also overdrives the valve at almost every of its settings.

Results

Each triode was tested on its own, which makes up a total of 22 triodes for the 11 valves. As can be seen in figure 43, there were some differences, but they were nowhere near enough to justify the huge differences in volume. The measurement was repeated with a few valves and an even higher input signal, hoping this would change something, but the results were about the same.

Conclusion

The differences in volume between the triodes were in the order of magnitude as one could have assumed based on the tests done before on V1. This is good because deviations from valve to valve which are as large as the Micro Dark implied would make the valve a very inconsistent and barely usable device for amplification. However, this leaves now the question why the perceived volume of the Micro Dark changes so much depending on the used valve.

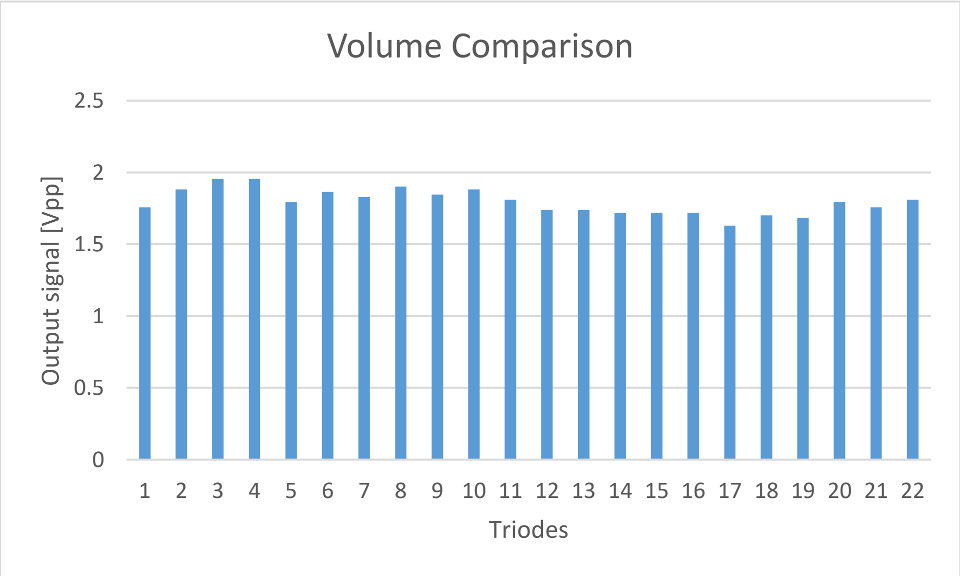


Figure 43: Volume comparison of all triodes in the test circuit.

4.7 Micro Dark

To find an answer to the question left unanswered by the last series of measurements, further measurements were made directly with the Micro Dark.

Procedure

Each of the 11 valves from the last test was used in the Micro Dark. Each valve was tested twice, once with the gain on the amplifier so low that there is no noticeable clipping, the other with the gain at the maximum. The input signal was applied at the amps input jack. The signal was 1 kHz 600 mVpp which is comparable to the output of a Humbucker guitar pickup. The settings for the volume and equalizer were the same for both tests. The volume was turned up all the way and the shape knob set to the middle position. The output signal was captured from the Fx-send of the Micro Dark.

Results

Figure 44 shows the output levels of all eleven valves in one diagram. The low gain signal was multiplied by forty to be comparable in the same diagram. The voltage differences between the different valves are humungous, sometimes about a factor of ten, which would result in a power factor 100, which is 20 decibels, which fits with the impression from playing the different valves. It is interesting that the ratio in output between the different valves is not the same at low and high gain settings, meaning there have to be differences in gain but also in headroom.

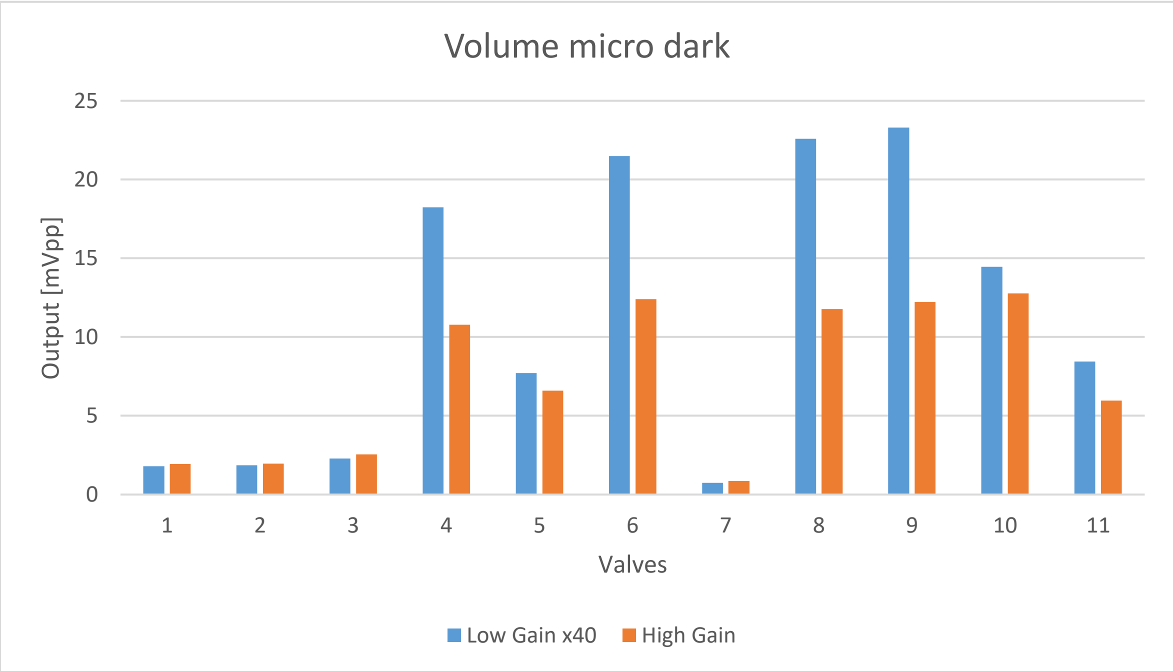


Figure 44: The differences between the test valves with high and low gain settings,

These measurements clash, however, with the ones from the test circuit. So, the Micro Dark was further investigated and checked with a multi meter. This showed that there is no charge pump circuit in the Micro Dark, which means the high potential for the valve is the same 15 volt the power supply delivers, which is far out of the range in which this valve is meant to operate.

Part	Voltage to ground [V]
Power supply	15.4
HT+	15.08
Anode V1A	12.56
Grid V1A	-0.24
Cathode V1A	0
Anode V1B	14.27
Grid V1B	-0.49
Cathode V1B	0
Anode V10A	2.98
Grid V10A	-0.35
Cathode V10A	0
Anode V10B	8.04
Grid V10B	-0.49
Cathode V10B	0

Table 1

Comparing a rather quiet valve (V1) to a louder one (V10) in table 1 shows that the bias and anode voltage are widely spread. Also, the cathodes being at zero volts means the triodes are not cathode biased. This leads to the conclusion that neither a common cathode bias nor fixed bias circuit was used but another circuit which seems to be very unreliable.

Discussion

The volume differences could have been successfully measured. These huge variances are caused by the much too small HT^+ of the Micro Dark and its inconsistent way of biasing the triodes. A nice addition to these measurements would be to do the same with different amplifiers which have a normal HT^+.

4.8 Output Transformer Linearity

The output transformer used in my amplifier was tested at different frequencies within the audio spectrum to determine its linearity.

Procedure

The input signal was applied at the 8 Ω tap of the secondary coil and the output measured at the anode connections of the primary coil. The input signal was 2 Vpp, starting at 100 Hz and roughly doubling it 9 times up to 25.9 kHz.

Results

The ratio between the signal at the primary and the signal at the secondary is very consistent with only the last measurement being considerably higher with a ratio 22.3. This can be seen in Figure 45.

While the ratio of the two signals stayed almost identical throughout the audio spectrum the actual magnitude of the signal measured at the secondary and therefore the one measured at the primary as well changed with the frequency. This can be seen in figure 46. However, this is assumed to be caused by the input and output impedance of the oscilloscope and the signal generator.

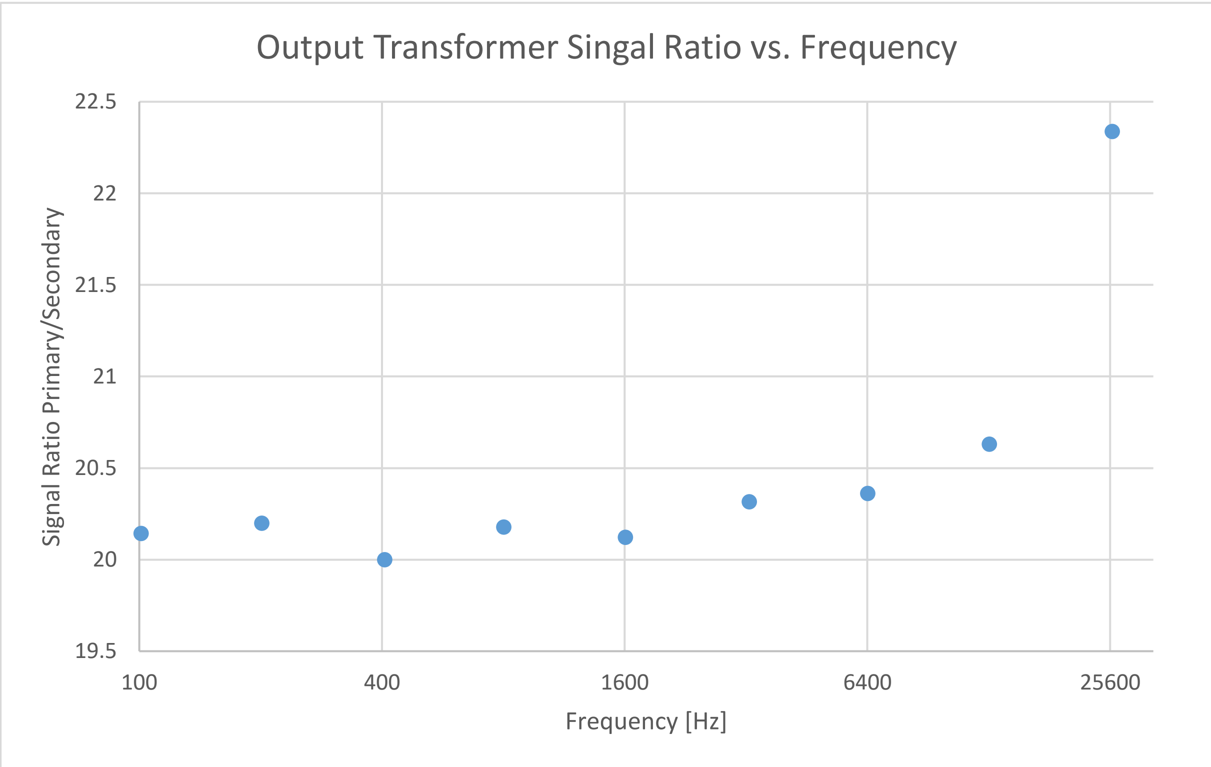


Figure 45: Transformer voltage ratio depending on frequency.

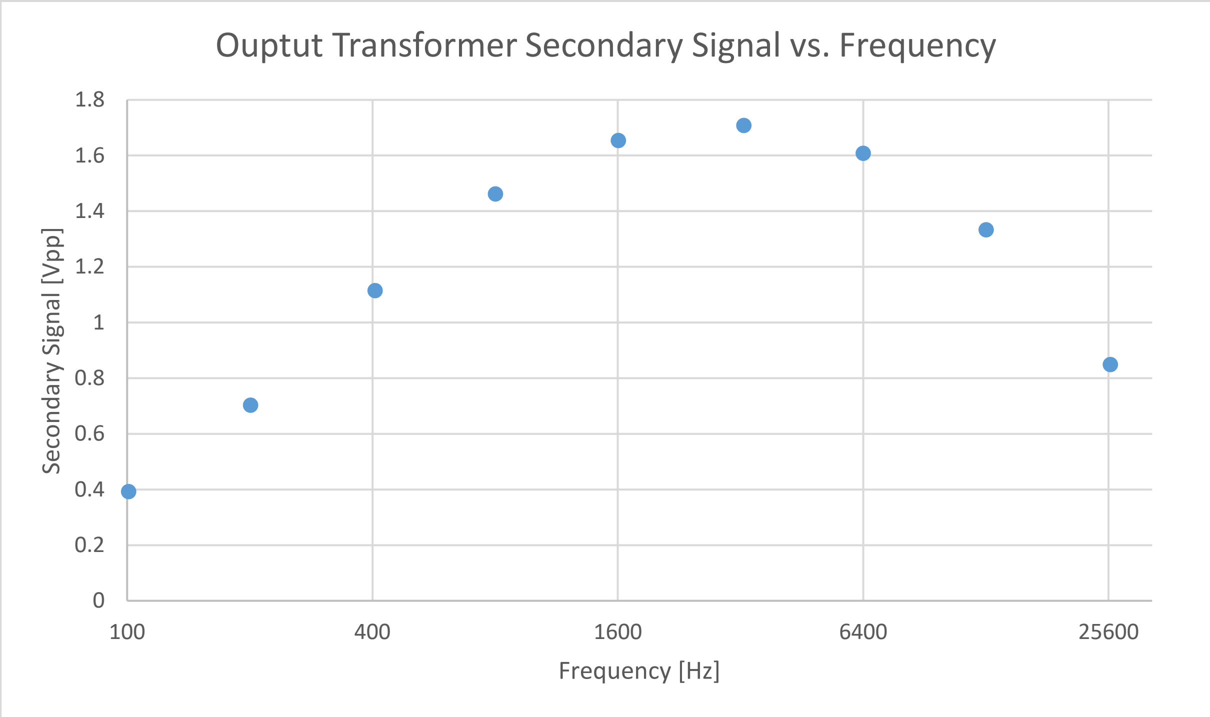


Figure 64: Magnitude of the signal measured at the secondary dependent on frequency.

Discussion

The output transformer reacts as it should in a very linear way to the different audio frequencies. For the frequencies which guitar speaker can reproduce which is up 6400 Hz. The maximal deviation from the ideal ratio of 20 was at 6400 Hz with +1.8%. Above 6400 Hz the ratio changes further but this is not important as the guitar speaker is very inefficient at those frequencies. This can be seen in figure 47.

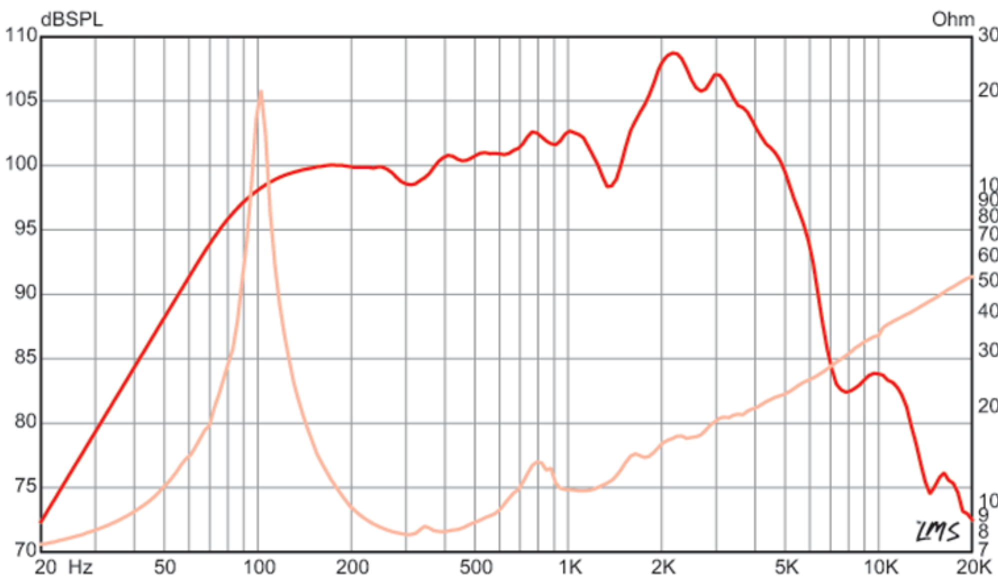


Figure 47: The frequency response (red) of an Eminence Governor speaker. Orange shows the impedance of the speaker. The graph is taken from the manufacturers website[17].

5. Conclusion

The primary goal of the project was to build a working valve amplifier. This goal was successfully achieved. While the amplifier did not end up exactly as planned at the beginning and there were many hurdles on the way, it had in the end everything a guitar amplifier needs and even offers some extra features, like the voice knob or the fx-loop.

Most of the problems encountered were not expected ones. It was anticipated to face more problems with the actual electronics of the amplifier, thus much time was invested into studying the theory. However, because of this, other problems which could occur, such as the physical arrangement of the components, were not considered enough. This resulted in the space management being one of the major problems of the whole construction process.

This shows that circuits do not only exist in schematics and books, but also need to be built, and simple tasks, like soldering wires, can take up much time if there are a lot of them. The crafting of the amplifier’s casing is another point like this. It has nothing to do with the electronics and it is no scientific challenge, but it still is part of the project and has consumed much time. If the amplifier was build outside of a casing with the sockets soldered directly to the boards, the whole project would have assumedly been much easier. The amplifier was built with the thought in mind that exchanging components would be easy. This may be true in theory, as replacing a resistor with another resistor is not really complex. In reality, this can be much more complicated, since there are wires, potentiometers and screws hindering the access.

The measurements were all successfully done and showed either expected or plausible results. It is especially nice that the reason behind the volume differences of the Micro Dark could have been found. The designed valve test circuit turned out to be a useful tool to compare different valves. There are many other things which could have also been measured, such as the frequency response of different valves, the effective output power of the GNR-50, the harmonics produced by the different kinds of distortion, the influence of the grid stopper on grid current clipping and so on.

However, this is maybe the problem of this project: it is too easy to include too many things. Whilst it started with the goal of the self-made amplifier which was already a reasonable project, more and more ideas about possible experiments came up. While working on the final report, it became unavoidably apparent that the theory part needed to be much larger than first intended to give the reader a reasonable insight and understanding of the matter.

In the end, those three parts moulded into the behemoth that this whole project became. As of this huge accumulation of topics and questions, it was unfortunately not possible to treat any of those three aspects with the care and attentiveness which could be considered as truly satisfactory and complete. What this report turned out to be is more a good overview over the world of valves and guitar amplification than a throughout scientifically substantiation of the whole matter.

It remains unclear whether it would have been wiser to focus more on one of the single parts. It would have been possible to put more focus on the evaluation of the experiments and the analysis of the amplifier however, this would have rendered this paper useless for everyone without any previous knowledge about valves. Another alternative would have been to put more focus on the theory, but this is not what was planned at first, since the focus of this project was on the practical part from the very beginning. The extended explanation of theory turned out to be more a bare necessity than anything else.

From my personal perspective the project was a success. I learned unbelievable many things which I am truly interested in. Although challenging and exhausting working on the amplifier was very satisfying, as not only the project, but also I myself made much progress. I could improve my soldering skills and my knowledge and understanding of valves and electronics in general. I started this project without any knowledge about valves and only very little experience with small signal transistor circuits and ended it with a functioning amplifier, and the fact that it sounds nice is a very pleasing bonus. This project reassured me in my plans to study electric engineering after the Matura and whilst I am happy to finally bring it to an end it, will definitely not be the last valve amplifier I will build.

6. Bibliography

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2 Blencowe, Merlin(2012): Designing Valve Preamps for Guitar and Bass, Second Edition, Wem Publishing

3 Vacuum Tube Electrodes: thermionic valve electrodes https://www.electronics-notes.com/articles/electronic_components/valves-tubes/electrodes-cathode-grid-anode.php [06.01.2019]

4 Philips ECC 83 data sheet

5 Philips EL 34 data sheet

6 Formeln Tabellen Begriffe, 5. erweiterte Auflage, Orell füssli Verlag 2015

7 All schematics were made with: EAGLE

https://www.autodesk.com/products/eagle/overview [06.01.2019]

8 Philips GZ34 data sheet

9 Lee De Forest (1913) The Audion – Detector and Amplifier

10 Simulations made with: Duncan's Amp: Tone Stack Calculator

http://www.duncanamps.com/tsc/ [06.01.2019]

11 Blencowe, Merlin: The Push-Pull Power Output Stage

http://www.valvewizard.co.uk/pp.html [06.01.2019]

12 Transformers and valve sockets were bought from: Tube Amp Doctor

https://www.tubeampdoctor.com/ [06.01.2019]

13 All the other electric parts were bought from: Distrelec

https://www.distrelec.ch/ch [06.01.2019]

14 JJ-Electronics ECC83s data sheet

16 Software used: Picoscope 6

https://www.picotech.com/downloads [06.01.2019]

17 http://www.eminence.com/guitar-bass/redcoat-series/ [06.01.2019]

7. Appendix

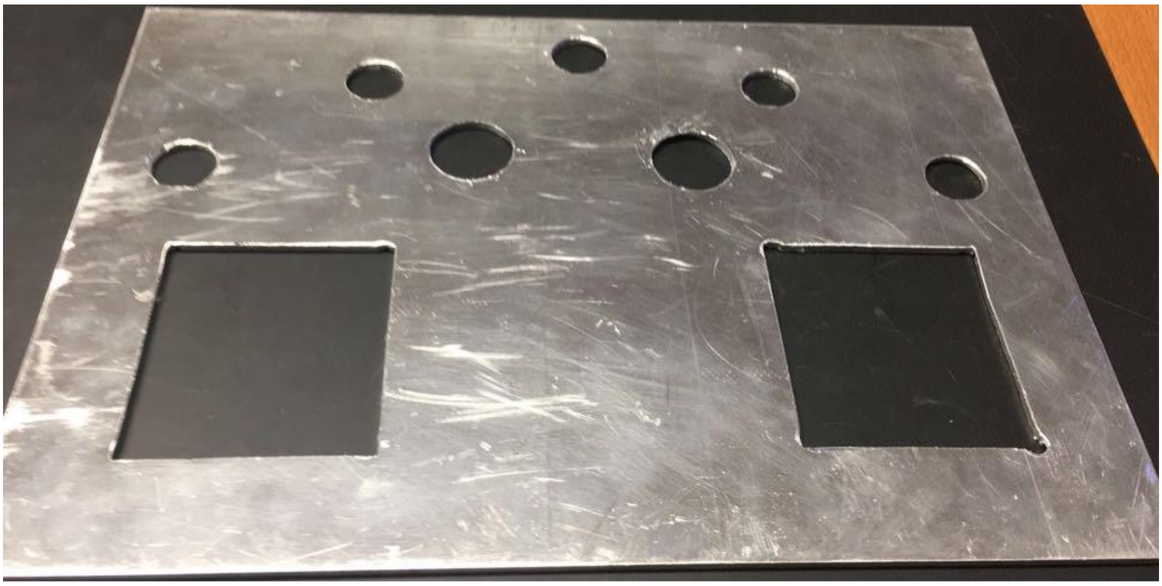

Figure 48: The top plate for the amplifiers case with holes for the transformers and valve sockets.

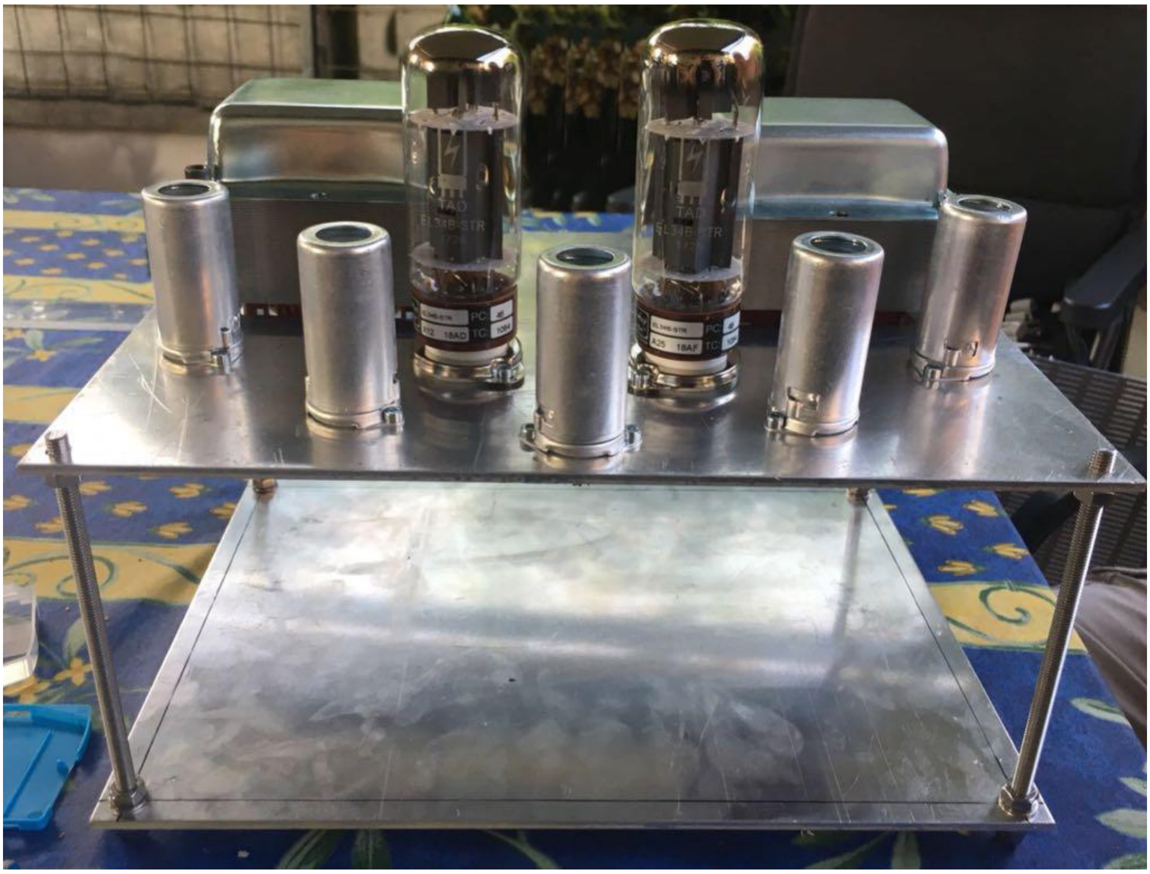

Figure 49: The finished case without the side walls.

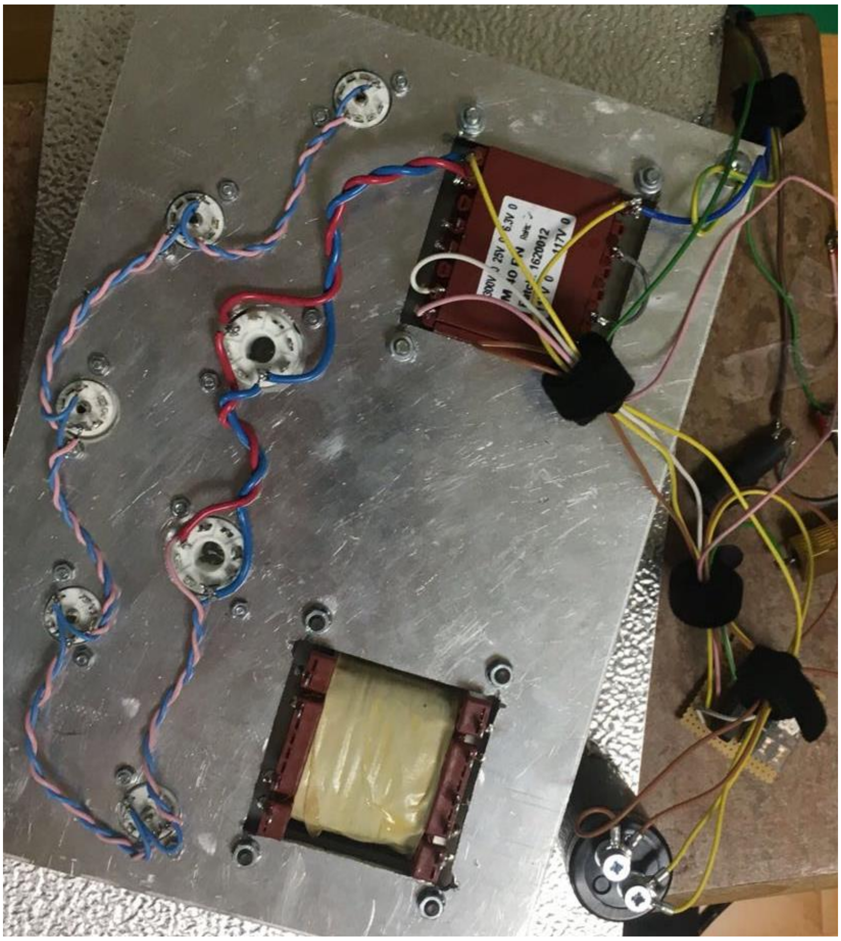

Figure 50: The wiring of the heater filaments

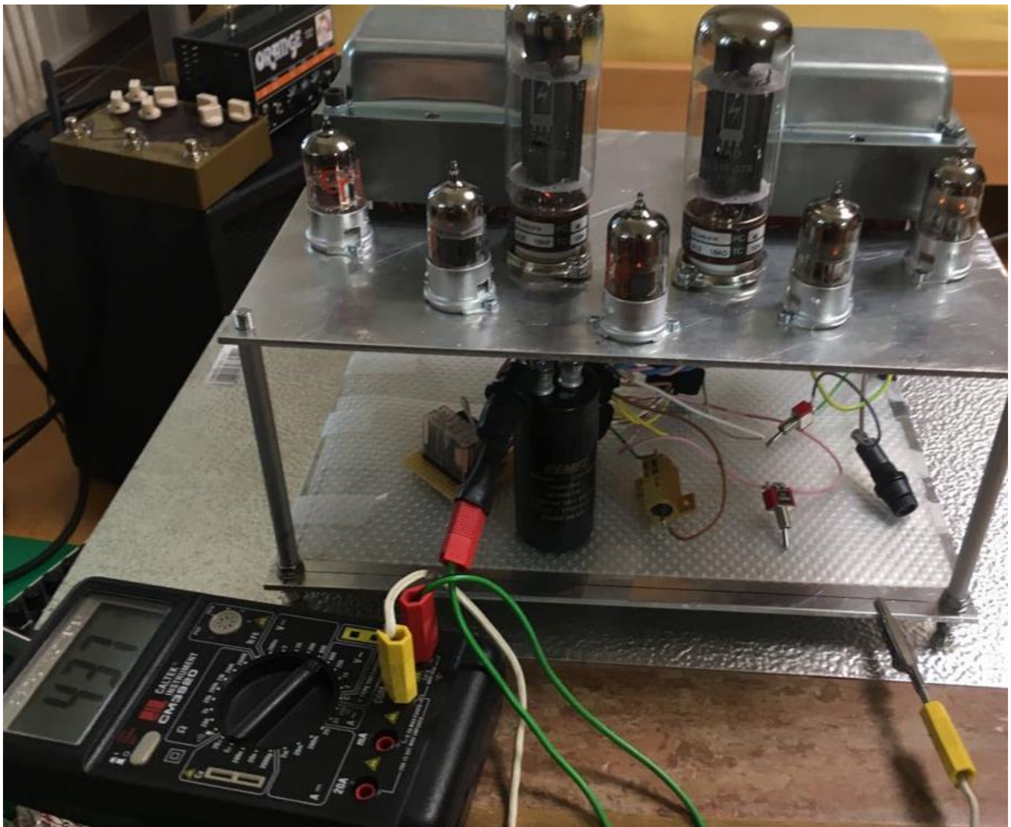

Figure 51: Testing of the power supply.

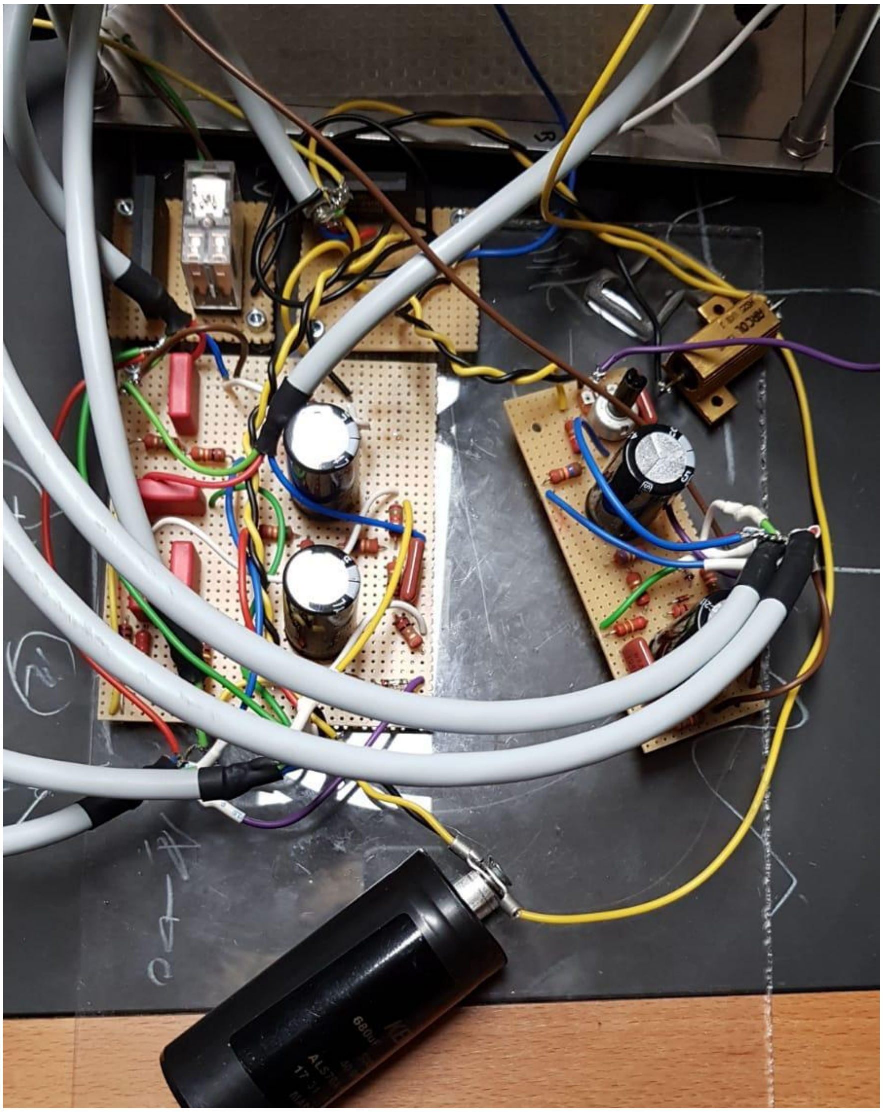

Figure 52: The circuit boards of the amplifier without the tone stack

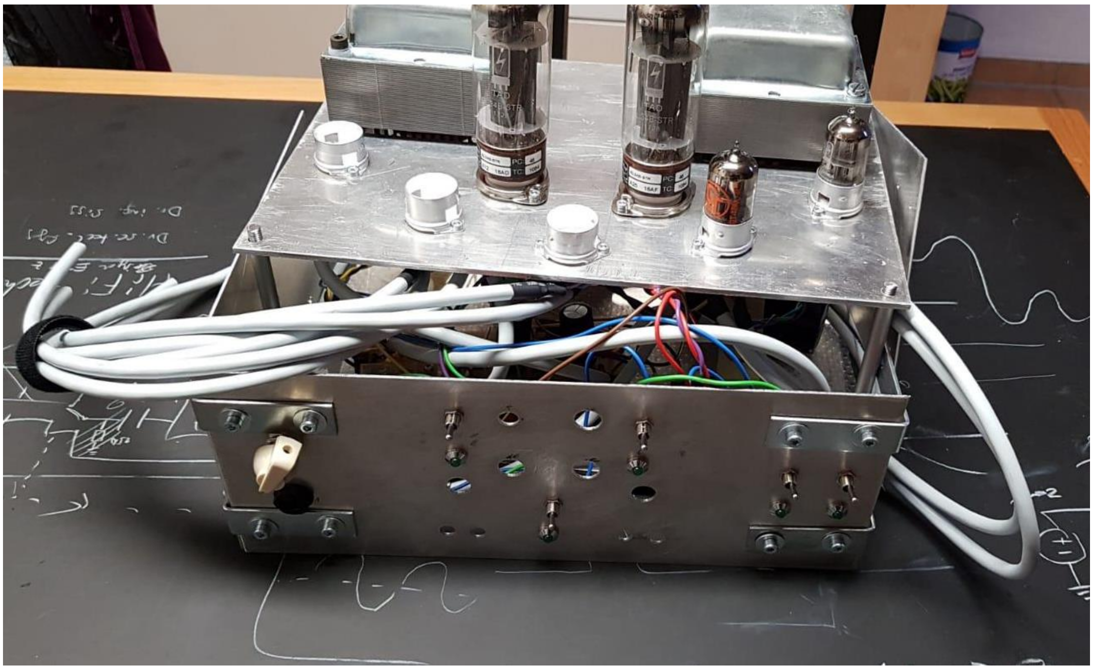

Figure 53: The amplifier with too many cables to fit in the casing.

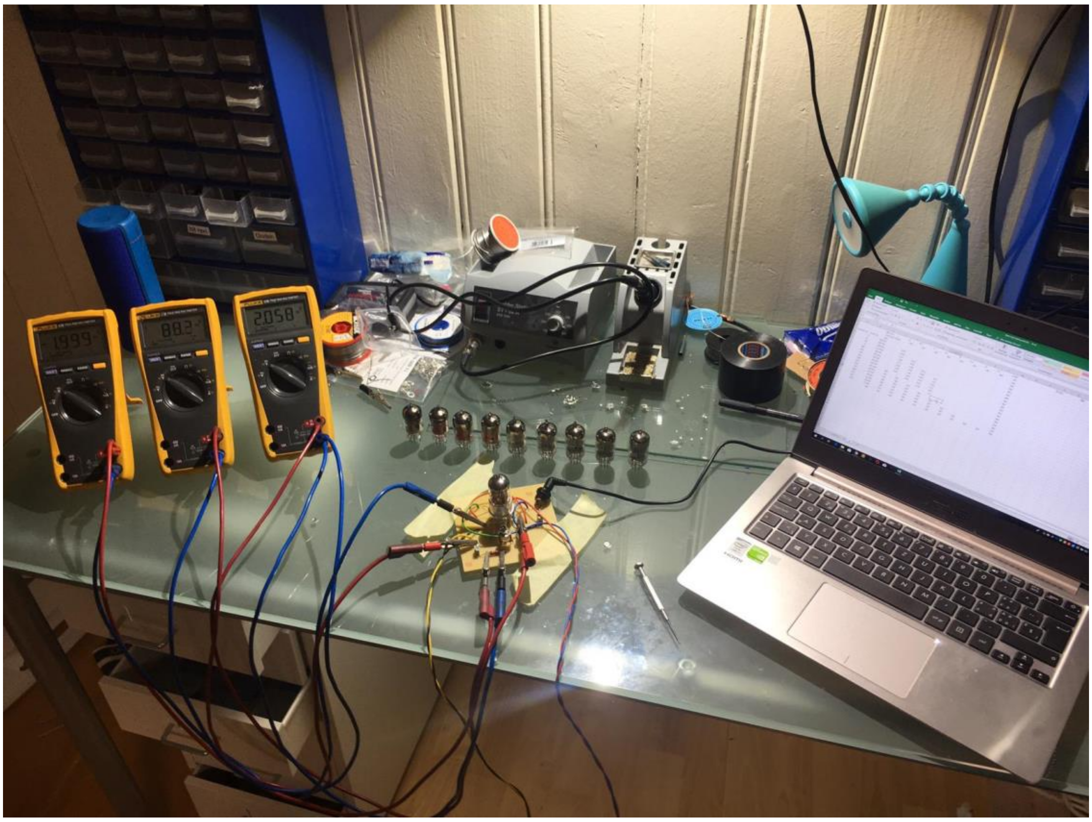

Figure 54: Experimental setup for the static valve tests.

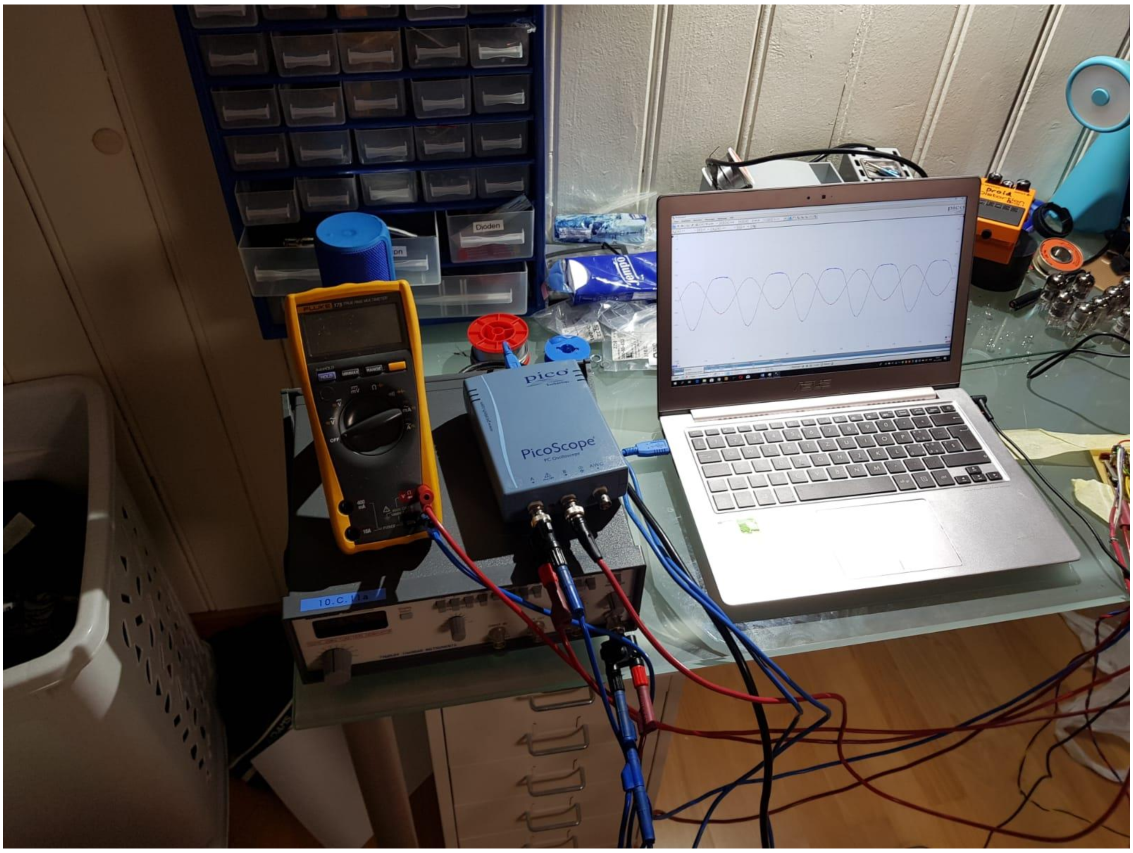

Figure 55: Experimental setup for the dynamic valve tests.

Valve	Brand	Exact Name
V1	JJ-Electronics	ECC83S
V2	Electro Harmonix	12AX7EH
V3	Groove Tubes	GT-12AX7-S
V4	Groove Tubes	GT-12AX7-R
V5	Groove Tubes	GT-12AX7-C
V6	Tube Amp Doctor	7025 WA
V7	Tube Amp Doctor	7025 WA
V8	Tube Amp Doctor	ECC83 WA
V9	Tube Amp Doctor	ECC83 WA
V10	Tube Amp Doctor	ECC83 WA
V11	Tube Amp Doctor	7025 WA

Table 2: The eleven test valves.

Va [V] V1A	Vshunt [V] (Vg=0V)	Vshunt [V] (Vg=-0.5V)	Vshunt [V] (Vg=-1V)	Vshunt [V] (Vg=-1.5V)	Vshunt [V] (Vg=-2V)	Vshunt [V] (Vg=-2.5V)	Vshunt [V] (Vg=-3V)	Vshunt [V] (Vg=-3.5V)	Vshunt [V] (Vg=-4V)
50	0.63	-	-	-	-	-	-	-	-
75	1.06	0.37	-	-	-	-	-	-	-
100	1.56	0.69	-	-	-	-	-	-	-
125	2.12	1.12	0.37	-	-	-	-	-	-
150	2.73	1.57	0.66	-	-	-	-	-	-
175	3.31	2.08	1.02	0.45	-	-	-	-	-
200	3.95	2.64	1.49	0.73	0.25	-	-	-	-
225	-	3.32	1.97	1.11	0.46	-	-	-	-
250	-	-	2.52	1.57	0.77	0.28	-	-	-
275	-	-	-	2.1	1.13	0.49	0.14	-	-
300	-	-	-	-	1.59	0.82	0.29	-	-
325	-	-	-	-	-	1.16	0.5	0.16	-
350	-	-	-	-	-	-	0.8	0.31	0.1
375	-	-	-	-	-	-	-	0.52	0.2

Table 3: Plate characteristics measurements V1A.

Va [V] V1A	Vshunt [V] (Vg=0V)	Vshunt [V] (Vg=-0.5V)	Vshunt [V] (Vg=-1V)	Vshunt [V] (Vg=-1.5V)	Vshunt [V] (Vg=-2V)	Vshunt [V] (Vg=-2.5V)	Vshunt [V] (Vg=-3V)	Vshunt [V] (Vg=-3.5V)	Vshunt [V] (Vg=-4V)
25	0.43	-	-	-	-	-	-	-	-
50	0.95	-	-	-	-	-	-	-	-
75	1.53	0.51	-	-	-	-	-	-	-
100	2.08	0.96	-	-	-	-	-	-	-
125	2.73	1.46	0.52	-	-	-	-	-	-
150	3.44	2.04	0.95	0.3	-	-	-	-	-
175	4.09	2.66	1.41	0.6	-	-	-	-	-
200	4.99	3.38	2.02	1.02	0.34	-	-	-	-
225	-	4.05	2.61	1.52	0.67	0.18	-	-	-
250	-	-	3.29	2.09	1.04	0.38	-	-	-
275	-	-	-	2.7	1.56	0.68	0.19	-	-
300	-	-	-	-	2.07	1.06	0.39	0.1	-
325	-	-	-	-	-	1.52	0.68	0.23	-
350	-	-	-	-	-	-	1.08	0.43	0.13
375	-	-	-	-	-	-	-	0.7	0.26

Table 4: Plate characteristics measurements V1A.

Ra [kΩ]	Output V1A [mVpp]	Output V1B [mVpp]
50	742	778.3
100	941.2	995.5
200	1032	1050
400	1086	1122

Table 5: Load measurements.

Bias [V]	Output V1A [mVpp]	Output V1B [mVpp]
-0.25	841.1	895.4
-0.5	949.6	985.8
-1	967.7	1013
-1.5	931.5	976.8
-2	895.4	922.5
-2.5	814	841.1
-3	723.5	759.7
-3.5	515.5	569.8
-4	388.9	461.3
-4.5	280.3	289.4

Table 6: Bias measurements.

Triode	Output [Vpp]
1A	1.756
1B	1.882
2A	1.955
2B	1.955
3A	1.792
3B	1.864
4A	1.828
4B	1.901
5A	1.846
5B	1.882
6A	1.81
6B	1.738
7A	1.738
7B	1.719
8A	1.719
8B	1.719
9A	1.629
9B	1.701
10A	1.683
10B	1.792
11A	1.756
11B	1.81

Table 7: Headroom measurements.

Valve	Output Low Gain [mVpp]	Output High Gain [mVpp]
1	45.01	1937
2	46.68	1955
3	57.29	2552
4	456.1	10790
5	193	6597
6	537.4	12410
7	18.64	862.6
8	564.5	11780
9	582.6	12230
10	361.3	12770
11	211	5969

Table 8: Micro Dark measurements.

Frequency [Hz]	Primary Signal [Vpp]	Secondary Signal [Vpp]
100.9	7.914	0.3929
201	14.21	0.7035
406	22.3	1.115
801	29.5	1.462
1605	33.28	1.654
3260	34.72	1.709
6410	32.74	1.608
12840	27.52	1.334
25900	18.98	0.8497

Table 9: Transformer measurements.

8. Eigenständigkeitserklärung

Der/die Unterzeichnete bestätigt mit Unterschrift, dass die Arbeit selbstsändig verfasst und in schriftliche Form gebracht worden ist, dass sich Mitwirkung anderer Personen auf Beratung und Korrekturlesen beschränkt hat und dass alle verwendeten Unterlagen und Gewährspersonen aufgeführt sind.