EE1L1 IP-1 Project Report

Power Supply Design

Group B2-1 PS1

TU Delft

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by

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EE1L1
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Nomenclature

Δt_{dis}	The time that the capacitor has to smooth the output voltage
ΔU_{dc}	The difference between the minimum and maximum voltage of the output waveform
$\frac{dV_C}{dt}$	The derivative of the voltage across the capacitor
τ	The time constant of the RC discharging circuit
C_1, C_2	The capacitance of the smoothing capacitors
I_C	The current through the capacitor
I_T	The current through the transformer
R_1, R_2	The resistance used to simulate the load
$R_{\text{dis,1}}$, $R_{\text{dis,2}}$	The resistance of the discharge resistors
t_{dis}	The time it takes for the capacitors to fully discharge
u_{average}	The average output voltage of the power supply under a constant load, calculated by taking the average of the minimum and the maximum voltage of the waveform
u_{max}	The maximum output voltage of the power supply under a constant load
$u_{\text{ripple}}[\%]$	A percentage to indicate the amount of ripple in the output voltage
$V+$	The output voltage on the positive output terminal of the power supply
$V-$	The output voltage on the negative output terminal of the power supply
V_{out}	The voltage at the positive output terminal of the power supply

Contents

1 Introduction

1.1. Introduction to the Power Supply

The Booming Bass Sound System consists of multiple subsystems, including the power supply, which is essential for its functionality. As its name implies, the power supply subsystem provides the necessary electrical power to support the operation of the entire sound amplification system and is a key component for the power amplifying subsystem. This report focuses on the power supply's design, simulation, and analysis, emphasizing the system requirements, design decisions, and methodologies implemented to achieve the specified and desired performance criteria.

1.2. Power Supply Properties

1.2.1. Power Supply Requirements

The power supply system must meet several critical requirements to ensure optimal and reliable operation of the sound amplifying system. These requirements are, therefore, essential for the proper functionality of the overall system, particularly in delivering consistent and stable power to the connected components. Below is a detailed list of the requirements that must be taken into account:

- **Unloaded output voltage**: Within a $\pm$ 20-22 V DC range on each positive and negative terminal side respective.
- **Unloaded Operation Discharge Time**: During operation without a load, the capacitors of the power supply should fully discharge within 2.5 minutes.
- **Load Output Voltage**: Under a load current of 1.0 A, the output voltage waveform should remain within 17-20 V DC.
- **Ripple Voltage**: The ripple voltage should not exceed 5%.
  Additional details and further analysis of the ripple voltage will be presented in the subsequent sections of the report.
- **Compatibility with Load Requirements** The requirements mentioned above should still be met under a 1.0 A load.

1.2.2. Power Supply Schematic

The power supply system's requirement and desired performance depend on design choices and decisions made during the project. Achieving the required performance for the Booming Bass Project necessitates careful consideration of various factors and parameters, including selecting the appropriate diodes, the values of multiple resistors, and the capacitance of smoothing capacitors. Each component mentioned must be chosen to ensure the power supply meets the specified requirements for voltage regulation, ripple percentage, and load performance.

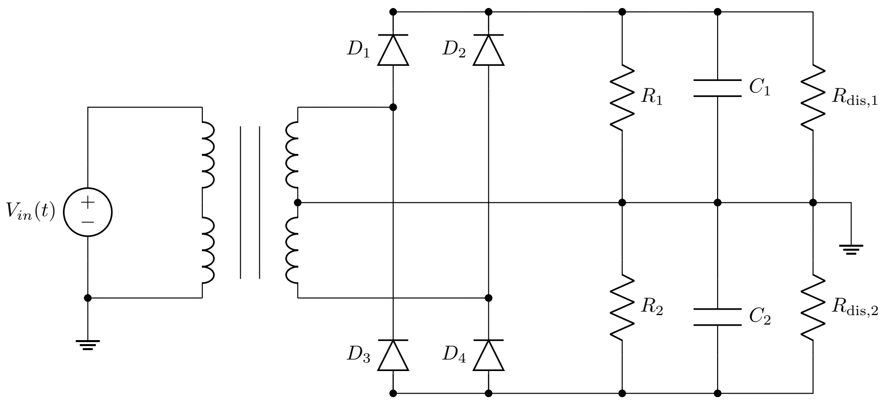

Figure 1.1: Complete schematic of the power supply.

Figure 1.1 shows the complete schematic of the power supply. Each element in the schematic is clearly labeled and serves a distinct function to meet the defined system requirements. It is clear from the schematic that the power supply is dependent on multiple factors and parameters and, thus, on their respective value. A brief explanation of these components is provided below. Additional details about their function will be presented in chapter 2.

- **Resistors R_1 and R_2**: These resistors will act and form the load of the power supply circuit, therefore simulating the load of real-world scenarios.
- **Resistors $R_{\text{dis,1}}$ and $R_{\text{dis,2}}$**: These resistors serve as discharge resistors, ensuring the safety of both the users and the capacitors by discharging the stored energy after each power supply operation.
- **Capacitors C_1 and C_2**: These capacitors are essential for smoothening the rectified DC output.
- **Diodes (1N5408)**: The diodes in the power supply circuit are responsible for the rectification process, converting the bidirectional flow of alternating current (AC) into the unidirectional flow of direct current (DC). This is essential for providing a DC voltage output.

1.2.3. Ripple Voltage

As mentioned, the smoothing capacitors filter out the ripple from the DC output voltage waveform after the rectifiers. Ripple voltage is a value expressed as a percentage, representing the difference between the maximum and average voltage, divided by the average voltage, and multiplied by 100%. The formula for calculating the ripple voltage is as follows [1]:

$$u_{\text{ripple}}[\%] = \left(\frac{u_{\text{max}} - u_{\text{average}}}{u_{\text{average}}}\right) \cdot 100\% \tag{1.1}$$

Further information regarding the ripple voltage and percentage can be found in the subsequent sectors, the Appendix, and the Integrated Project-1 Manual.

2 Design Methodology

2.1. Design Procedure

The design procedure for the power supply circuit and system begins with defining the system requirements and a rough understanding of the operating conditions for the Booming Bass Sound System. This was already done in chapter 1. The primary goal is to design a power supply that efficiently converts the AC voltage from the main outlet through a center-tapped transformer into a stable DC voltage waveform, thus capable of powering and providing power to the entire sound amplifying system.

2.1.1. Circuit Component Selection

With the power supply requirements in mind, the next step was to dimension the components to meet the requirements. After that, it was needed to select components from the available ones. The components to be selected for the design included:

- **Transformer**: A center-tapped transformer to provide a dual output voltage necessary for the full wave rectification process. The transformer, therefore, provides both a positive and a negative output.
- **Capacitors**: Smoothing capacitors are used to filter the ripple in the DC output. Since the center-tapped transformer provides both positive and negative outputs at the terminals, two smoothing capacitors are employed: one for the positive voltage and the other for the negative output voltage. It is needed to calculate the needed capacitance of those capacitors.
- **Resistors**: The resistors in the power supply act as discharge resistors. Therefore, it was needed to select the correct resistor to make sure the capacitors were discharged within the specified time.

2.1.2. Analysis, Testing & Measurements

The results obtained from simulating the circuit in LTSpice should provide valuable insight into the expected performance of the power supply and what to expect from the power supply.

After analyzing the expected performance of the power supply through circuit simulations, testing and measurements of the assembled power supply must be conducted to verify that its real-world performance aligns with the predicted outcomes.

Those measurements will be done using the following devices:

- **Oscilloscope: Tektronix TDS 2022B**: An oscilloscope will be necessary to conduct analysis and measurements after building the power supply to check the performance of the power supply.
- **Load resistors**: Large resistors are used to simulate the load of the power supply.

2.1.3. Final Design

If the results align with the requirements of the power supply and meet the desired specifications and results, no additional changes and modifications are necessary to the power supply circuit, and the circuit can be used in the sound system.

2.2. Circuit Elements and Components

The performance of the power supply system depends heavily on design decisions made throughout the project. Achieving the desired performance for the power supply requires careful consideration of various factors, such as the selection of diodes, the values of resistors, and the capacitance of smoothing capacitors. Each component's value must be chosen to ensure the power supply meets the specified requirements for voltage regulation, ripple percentage, and load performance. The complete schematic of the circuit is provided in Chapter 1, but for convenience, it is also included here:

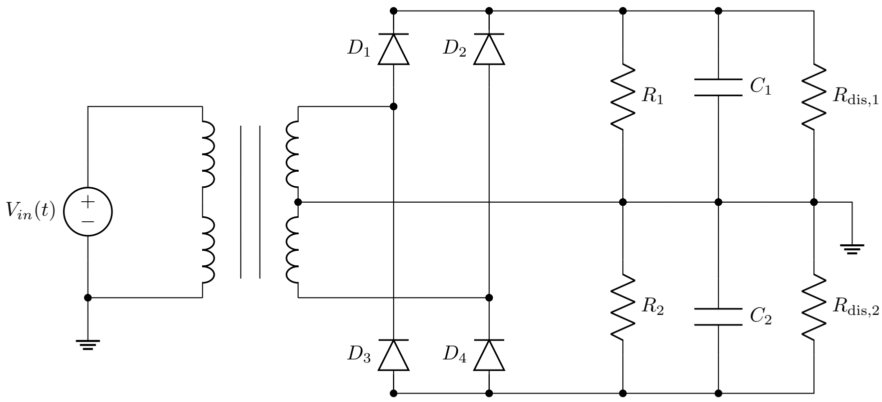

Figure 2.1: Complete schematic of the power supply.

The complete schematic of the power supply is shown in Figure 2.1. Each element in the schematic is labeled and serves a distinct function to meet the defined system requirements. It is clear from the schematic that the power supply is dependent on multiple components and, thus, on their respective value.

- **Resistors R_1 and R_2**: These resistors act and form the load of the power supply circuit, therefore simulating a real-world load. The values of the load resistors are based on the equivalent resistance of the sound-amplifying system and are thus selected for testing to ensure that the output voltage remains within the desired range (i.e. 17-20 V DC) when a load current of 1.0 A is applied to the power supply circuit.
- **Resistors $R_{\text{dis},1}$ and $R_{\text{dis},2}$**: These resistors serve as discharge resistors, ensuring a safe environment after operation by discharging the stored energy in the capacitors. These resistors should allow the power supply to be fully discharged within 2.5 minutes after operation.
- **Capacitors C_1 and C_2**: These capacitors are essential for smoothing the rectified AC input, functioning as energy storage to reduce ripple in the outgoing DC voltage at each terminal. In the power supply circuit, the AC voltage from the transformer undergoes rectification through the diodes, but fluctuations are still present in the DC output. These fluctuations are referred to as ripple. Capacitors C_1 and C_2 charge during the peaks of the DC waveform and discharge during the troughs, effectively ensuring that the DC voltage remains as stable as possible. The difference between the maximum and minimum capacitor voltage is thus called the ripple voltage. The choice of the capacitance values C_1 and C_2 and the load current determines the degree of ripple reduction and, thus, the overall stability of the output.
- **Diodes (1N5408)**: The power supply circuit diodes are responsible for rectifying the AC input into a unidirectional DC output. The actual diodes are already soldered on and differ from those chosen in the simulation process; the standard 1N4148 diodes are chosen in the LTSpice simulations for convenience. While they differ in primary characteristics, the 1N5408 diodes are more resilient than the 1N4148 regarding maximum repetitive peak voltage and maximum RMS voltage.

2.2.1. Dimensioning Circuit Components and Elements

2.2.1.1. Smoothing Capacitors

Using the equation provided earlier in Chapter 1.2.3 for $u_{\text{ripple}}[\%]$, it is possible to calculate a maximum voltage to have a ripple less than 5%, assuming an average voltage of 19V.

$$u_{\text{ripple}}[\%] = \left(\frac{u_{\text{max}} - u_{\text{average}}}{u_{\text{average}}}\right) \cdot 100\% \quad (2.1)$$

Rearranging equation 2.1 yields the following expression for u_{max}:

$$u_{\text{max}} = u_{\text{average}} \left(1 + \frac{u_{\text{ripple}}[\%]}{100\%}\right) \quad \text{(V)} \quad (2.2)$$

Equation 2.2 remains dependent on the average voltage and the ripple percentage. Therefore, the maximum voltage can be calculated for an average voltage of 19V after rectification, which gives us $u_{\text{max}} = 19.95V$.

From this result, it is clear that the maximum voltage must not exceed 19.95 V to ensure that the ripple voltage remains within 5% of the average voltage. With this constraint and limitation in place, the necessary capacitance value to keep the ripple voltage under 5% can be determined and calculated. This calculation is based on a maximum post-rectification voltage of 19 V and during a load current of 1.0 A, using the voltage-current relationship for a capacitor:

$$I_C = C_{1,2} \frac{dV_C}{dt} \quad \text{(A)} \quad (2.3)$$

For this calculation, an approximation of the exponential decay of the voltage across the capacitor is applied. It is assumed that this decay follows a linear behavior. Therefore, the following approximation can be made:

$$\frac{dV_C}{dt} \approx \frac{\Delta U_{\text{dc}}}{\Delta t_{\text{dis}}} \quad (2.4)$$

By combining equations 2.3 and 2.4, the voltage-current relationship for the capacitor can be rewritten as follows:

$$I_C = C_{1,2} \left(\frac{\Delta U_{\text{dc}}}{\Delta t_{\text{dis}}}\right) \quad \text{(A)} \quad (2.5)$$

By using equation 2.5 and $u_{\text{max}} - u_{\text{average}} = \frac{1}{2}\Delta U_{\text{dc}}$ [1], it can be said that:

$$C_{1,2} = I_C \left(\frac{1}{\left(\frac{\Delta U_{\text{dc}}}{\Delta t_{\text{dis}}}\right)}\right) = I_C \left(\frac{\Delta t_{\text{dis}}}{\Delta U_{\text{dc}}}\right) = I_C \left(\frac{\Delta t_{\text{dis}}}{2\left(u_{\text{max}} - u_{\text{average}}\right)}\right) \quad \text{(F)} \quad (2.6)$$

Therefore, the required capacitance to achieve a ripple voltage below 5% can be calculated with formula 2.5. Filling in $\Delta t_{\text{dis}} = 0.01s$ (half a period of 50 Hz), $u_{\text{max}} = 19.95V$, $u_{\text{average}} = 19.00V$ and $I_C = 1.0A$ gives a minimum capacitance of $5.263mF$.

It is important to note that the calculated capacitance values apply individually to both the power supply circuit's positive and negative output terminals. Consequently, the two capacitors of equal capacitance are required to ensure proper functionality on either side of the output terminal.

2.2.1.2. Discharge Resistors

For the effective operation of the power supply and to ensure the safety of the smoothing capacitors, discharge resistors play a crucial role. Their value can be determined using the time constant of the power supply, which behaves as an RC circuit. The calculation is based on the following equation, where $i = 1, 2$ respective to each discharge resistor and each smoothing capacitor:

$$\tau = R_{\text{dis,1 dis,2}} C_{1,2} \qquad \text{(s)} \quad (2.7)$$

As for the power supply circuit, the smoothing capacitors are assumed to be fully discharged after approximately 5τ. Thus, it is assumed that $5\tau \approx s_{\text{dis}}$, where t_{dis} represents the discharge time. In this case, the capacitors of the power supply should be discharged within 2.5 minutes, meaning that $t_{\text{dis,max}} = 150s$. Rewriting equation 2.7 for R_{i} gives:

$$R_{\text{dis,1 dis,2}} = \frac{\tau}{C_{1,2}} = \left(\frac{\left(\frac{t_{\text{dis}}}{5}\right)}{C_{1,2}} \right) = \frac{t_{\text{dis}}}{5C_{1,2}} \qquad (\square) \quad (2.8)$$

Using formula 2.8, the previously calculated capacitance, $t_{\text{dis}} = 150s$ gives a discharge resistor of $5.7k\Omega$.

A discharge resistance of $5.7k\Omega$ for $R_{\text{dis,1}}$ and $R_{\text{dis,2}}$ respective ensures that the power supply fully discharges within 2.5 minutes, given a smoothing capacitance of $5.263mF$ at each side of the output terminals. This calculation and the corresponding equation 2.8 show that reducing the discharge resistance will result in a shorter discharge time for the power supply.

3

Simulation results

3.1. LTSpice Simulation

In this chapter, LTSpice simulations were created using the values partially gained from calculations 2.6 and 2.8. However, those values weren't available. Therefore, deviations were made from the values presented previously; for the capacitor, a value of $6.8mF$ was chosen, and for the discharge resistors, a value of $3.9k\Omega$ was chosen. Further elaboration and information regarding the choice of values will be presented in the subsequent sections and chapters.

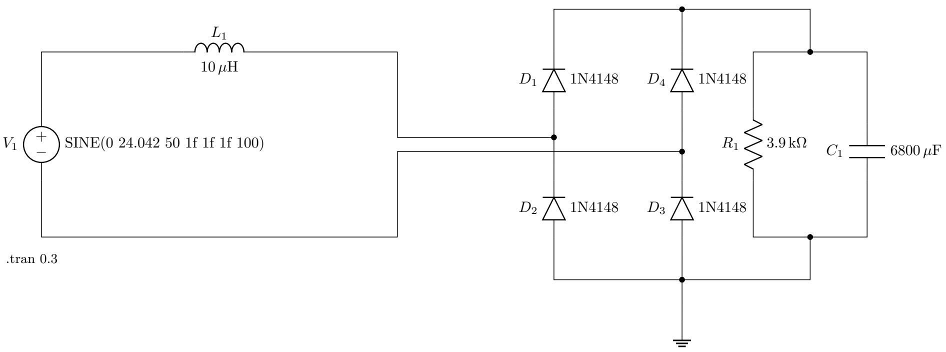

Figure 3.1: The schematic of the circuit that was simulated in LTSpice.

As previously discussed, the LTSpice simulations were performed for only one output terminal, as the use of a center-tapped transformed allows the existence of symmetry of the power supply; this ensures consistent behavior on both the positive and negative output terminals. This means that analysis on only one side of the output terminal is sufficient. Next to that, the transformer was replaced by an AC voltage source with a inductor in series to model the non-ideal transformer. The model of the circuit used in LTSpice can be seen in figure 3.1.

Table 3.1: Characteristics of the power supply in simulation under various levels of load.

Resistance Load [Ω]	Average Voltage [V]	Average Current [A]	Ripple [%]
19 Ω	18.3	0.963	2.58
38 Ω	19.6	0.516	1.43
76 Ω	20.5	0.27	0.78
Open	22.3	0.00	0.55

Table 3.1 presents the simulation results for the power supply operating under different resistive load conditions. The data includes each load's average output voltage, current, and ripple percentage.

The ripple percentage was calculated using equation 2.1. All the values were calculated by using the code in appendix C.1. These simulation results demonstrate how the power supply responds to varying loads, providing insight into its ability to maintain consistent performance and stability across different operational scenarios and various load levels.

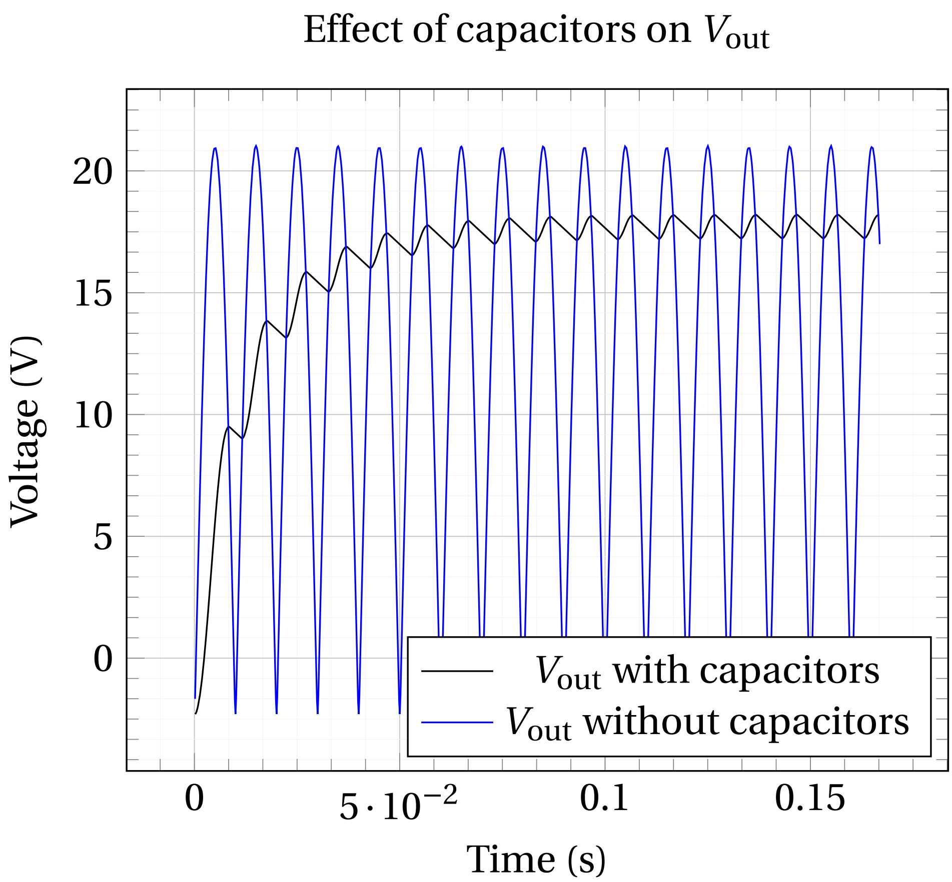

Figure 3.2: The simulated circuit output voltage. The blue line represents the circuit without any smoothing capacitors, while the black line represents the circuit with them present.

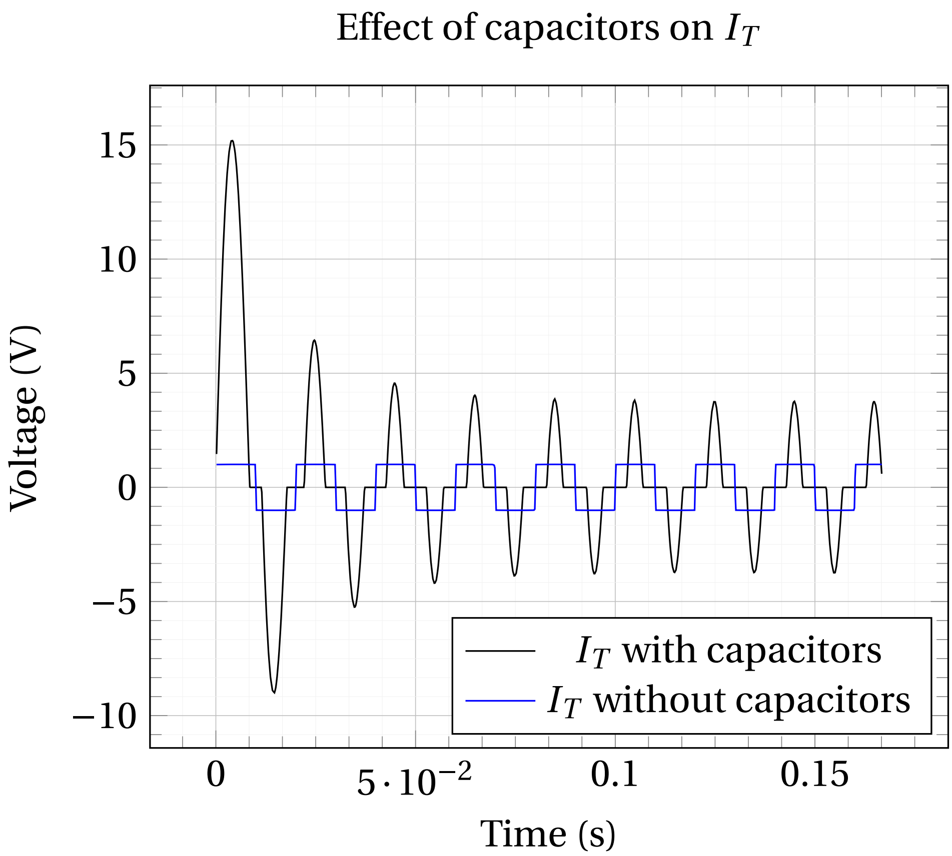

Figure 3.3: The simulated circuit current through the transformer. The blue line represents the circuit without any smoothing capacitors, while the black line represents the circuit with them present.

Figures 3.2 and 3.3 clearly demonstrate the impact of the smoothing capacitors on the output voltage and current waveforms. In figure 3.2, the absence of smoothing capacitors results in the output voltage remaining a rectified sinusoidal shape. Conversely, the inclusion of smoothing capacitors produces an output voltage waveform that resembles a steady DC voltage signal a lot closer.

4
Power Supply Assembly

4.1. Main Power Supply PCB

This chapter outlines the step-by-step process for assembling the power supply circuit, ensuring accurate implementation of all components and elements. The Power Supply Assembly procedure includes soldering on the smoothing capacitors C_1 and C_2 and the discharge resistors $R_{\text{dis},1}$ and $R_{\text{dis},2}$. The selection and dimensioning of each component within the power supply circuit have been addressed in the preceding sections of this report.

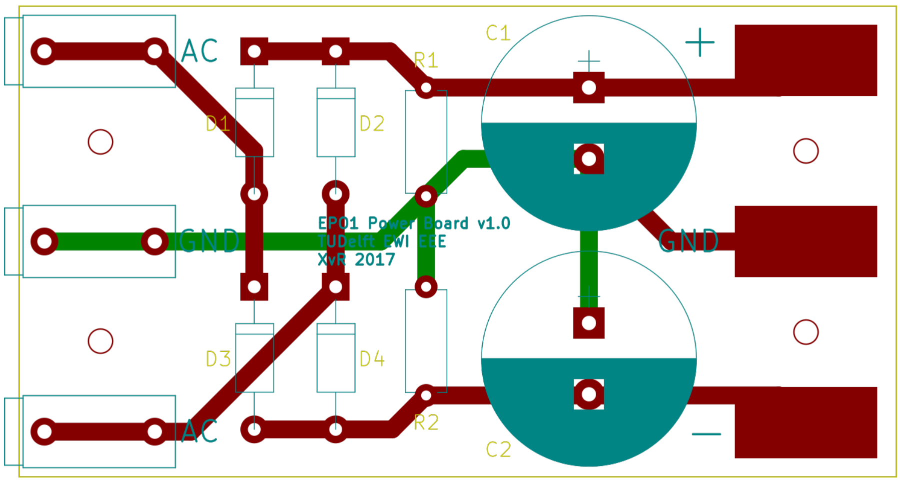

Figure 4.1: The layout of the power supply PCB. The positions in yellow and cyan correspond to the respective names of the components used in this report.

The PCB layout above illustrates the designated locations for each component discussed, where the diodes responsible for the rectification process were pre-soldered. The power supply's positive and negative output terminals are located on the right side of the circuit, as can be seen in figure 4.1.

4.1.1. The Smoothing Capacitors

As previously discussed in Chapter 1 and Chapter 2, the capacitors in the power supply are used to smoothen out the voltage waveform after rectification. The capacitors achieve this by storing energy during the peaks of the DC voltage waveform and releasing it during the troughs, effectively reducing the fluctuations and, therefore, ensuring a more stable output voltage. Based on formula 2.6 in chapter 2, it is evident that a capacitance of $5.263mF$ is required on each output terminal of the power supply to maintain ripple voltage below 5%.

In reality, the available capacitor values options were limited to $4.7mF$ or $6.8mF$. Still, as previously discussed, a higher capacitance results in reduced ripple, leading to a more stable DC output voltage waveform. The capacitance's value is important since it directly dictates the magnitude of the smoothening. A higher capacitance ensures a more stable output voltage waveform. For this reason, the $6.8mF$ capacitor was chosen as the value for the smoothing capacitors.

4.1.2. Discharge Resistors

As previously discussed in Chapter 2, the discharge resistors in the power supply are responsible for the safe discharge of the capacitors after power supply operation. Based on calculation 2.8, it is evident that a resistance of $5.7k\Omega$ is required. However, as discussed in section 4.1.1, it was needed to use a $6.8mF$ capacitor. This results in a maximum discharge resistance of $4.4k\Omega$. The resistor that was available and lower than, but near to $4.4k\Omega$, was a $3.9k\Omega$ resistor. Therefore, a $3.9k\Omega$ resistor was used.

4.1.3. The Load Resistors

Load resistors were utilized to simulate a load current of 1.0 A on the power supply circuit while maintaining a minimal rectified voltage of 17 V. These components were readily available and required minimal handling by connection via banana cables for integration to the power supply.

5 Measurement results

Multiple measurements were done to characterize the power supply and to measure its performance. The following characteristics and scenarios were measured:

- The average output voltage under various levels of load.
- The ripple in the output voltage under various levels of load.
- The capacitors' discharge time after power supply operation.

5.1. Average Voltage and Ripple

The voltage waveform across the load resistors R_1 and R_2 was measured under four distinct conditions to evaluate the ripple voltage. These measurements aimed to analyze the behavior of the power supply under varying load scenarios, where R_1 and R_2 simulate the operational load conditions of the circuit. Table 5.2 outlines the different test conditions.

Table 5.1: Different conditions under which the ripple and average voltage were measured.

- **Resistors in Series**
  With the output terminals connected to two 38 Ω resistors in series, thus forming a 19 Ω resistor as an equivalent resistor.
- **Single Resistor**
  With the output terminals connected to a single 38 Ω resistor.
- **Resistor in Parallel**
  With the output terminals connected to two 38 Ω resistors in parallel, forming a 76 Ω resistor as an equivalent resistor.
- **No Load Resistors**
  With no load on the output terminals.

The graphs of the measurements can be seen in appendix B.1. When conducting those measurements, only the positive side of the power supply was loaded because the negative side is an exact copy of the positive one. Support for this claim in practice can be found in appendix B.2. Those measurements were done by connecting the probe to the ground and the positive output of the power supply (and measuring the voltage over the resistors).

Those measurements led to the characteristics seen in table 5.2. The ripple was calculated using formula 1.1. The code in appendix C.2 was used to calculate the values in table 5.2.

The ripple for the open circuit is most likely just a measurement error of the oscilloscope because the oscilloscope was set to have a resolution of 0.04 V. In the measurements, the maximum voltage is 23.04 V, and the average voltage is 23.00 V. Although there would have been a small ripple due to the capacitors slowly discharging through the discharge resistor, the ripple induced by this current was insignificant compared to the one measured, as the discharge current is very small.

Table 5.2: Characteristics of the power supply under various levels of load.

Resistance Load [Ω]	**Average Voltage [V]**	**Average Current [A]**	**Ripple [%]**
19 Ω	20.1	1.06	3.23
38 Ω	21.1	0.56	1.66
76 Ω	21.9	0.29	1.10
Open	23.0	0.00	0.26

As can be seen by comparing the simulation table with the table above, it is clear that there is a significant discrepancy between the simulation and measurement results. This can be attributed to various factors:

- The diodes used in the simulation differ from those used in reality. The 1N4148 diodes used in the simulation are general diodes and are not fitted to carry large currents [3]. The 1N5408, on the contrary, can carry average rectified currents up to 3.0 A [2]. Therefore, the 1N5408 will result in much less loss over the diode. This can also be seen by comparing tables 3.1 and 5.2. In those tables, it can be seen that the difference becomes bigger as the current increases.

- The output voltage of the transformer is bigger than the voltage that was used to simulate the input. The simulated voltage was $17V_{rms}$, but $17.25V_{rms}$ was measured on the output. This will result in a small error.

- In the simulation, an $10mH$ inductor was placed in series with the voltage source to simulate the impedance of the transformer. This will be a little off, resulting in a small error too.

5.2. Discharge Time Capacitors

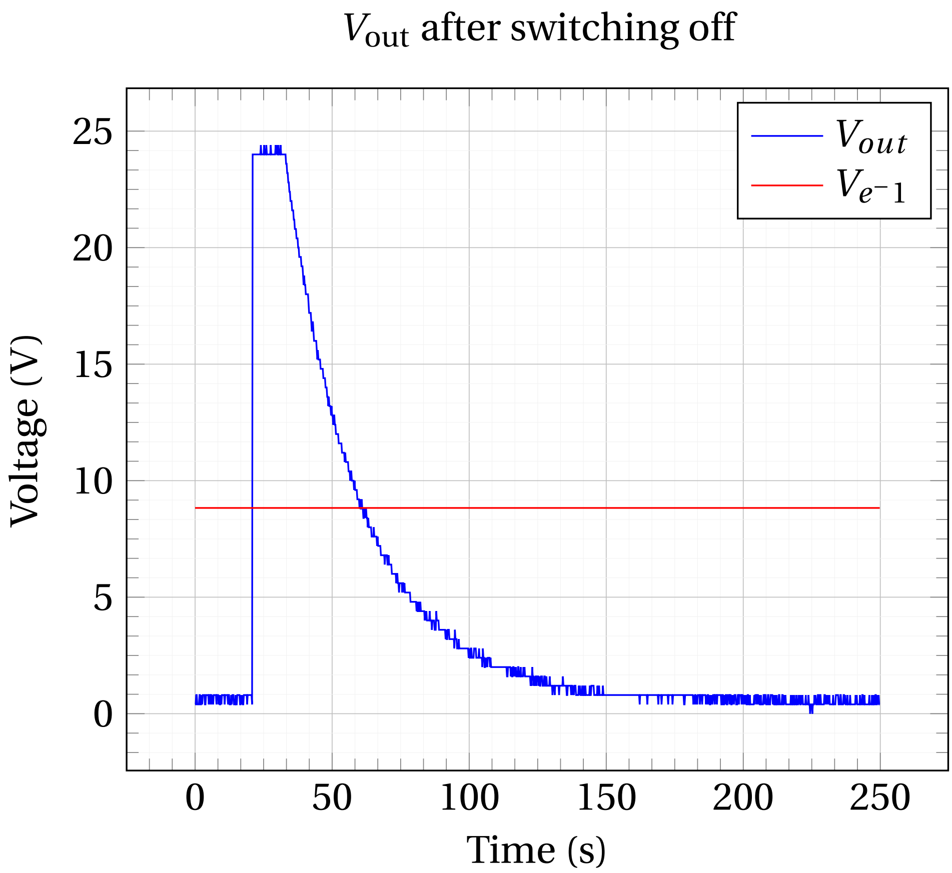

Figure 5.1: The discharge curve of the capacitors, measured at V_{out}.

From figure 5.1, it can be seen that the capacitors are disconnected from the power supply at $t = 33.0s$. The curve crosses the red line (which indicates the point that τ is 1) at $t \approx 62s$. This means $\tau \approx 28s$, which means that the capacitors will be discharged after 145 seconds, which fits nicely in the 2.5-minute limit it was designed for.

6 Conclusions

To conclude, the design of the power supply was a success and fits most requirements. The capacitors are able to discharge within 2.5 minutes after operation, under a load current of 1.0 A, the output voltage is well within the specified range. The ripple in the voltage is less than 5% and this also holds under 1.0 A of load. The only requirement which is not fully met, is the requirement that the unloaded output voltage should be in the 20-22 V DC range. The unloaded output voltage is 23 V DC, which is a bit above the range, but will be nog problem.

In the future, one could look into a bit lower unloaded output voltage, but this is quite pointless, as this will not have any further impact on the speaker.

Overall, this project was a success and the power supply can now successfully be integrated into the sound system.

Bibliography

[1] Dr.ir. G.J.M. Janssen et al. *Integrated Project 1 (IP-1) EE1L1 ”Booming Bass (Sound) System”*. Delft University of Technology. 2024.

[2] *Power Diode*. 1N5408. Multicomp. May 2005. URL: `https://www.farnell.com/datasheets/314353.pdf`.

[3] *Small Signal Diode*. 1N4148. Fairchild. June 2015. URL: `https://docs.rs-online.com/0981/0900766b8170974f.pdf`.

A

Simulations

A.1. Average Voltage and Ripple Simulation Results

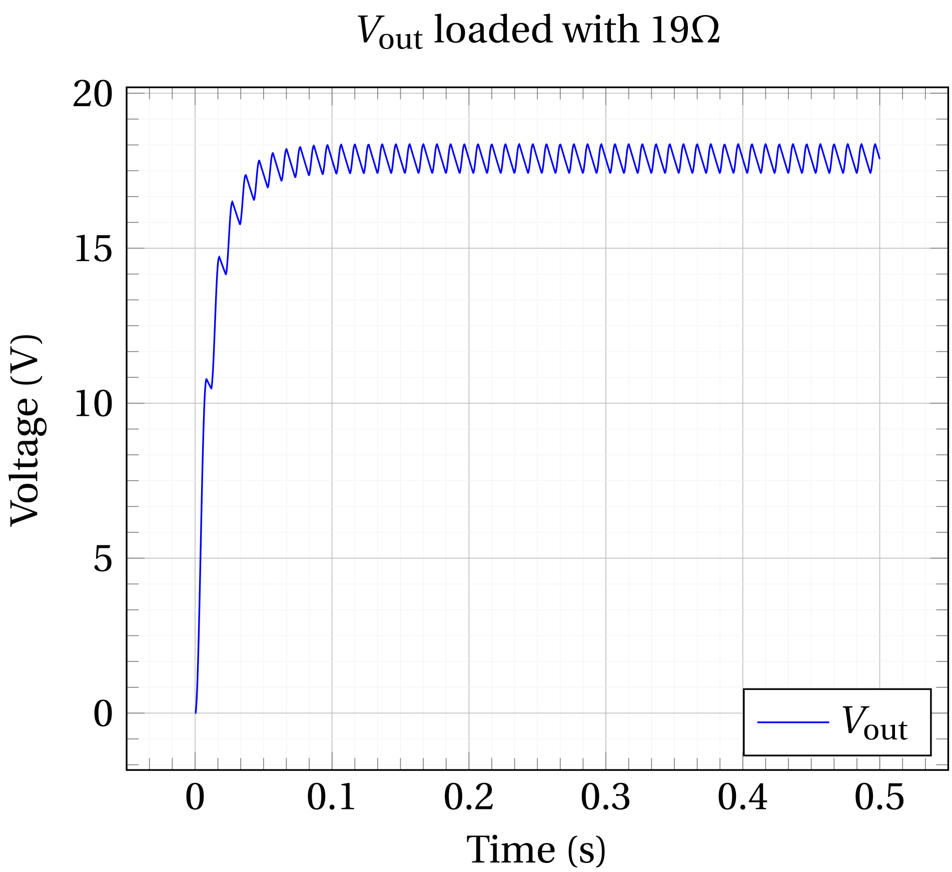

Figure A.1: The output voltage waveform of the simulation with the power supply loaded with a 19 Ω resistor.

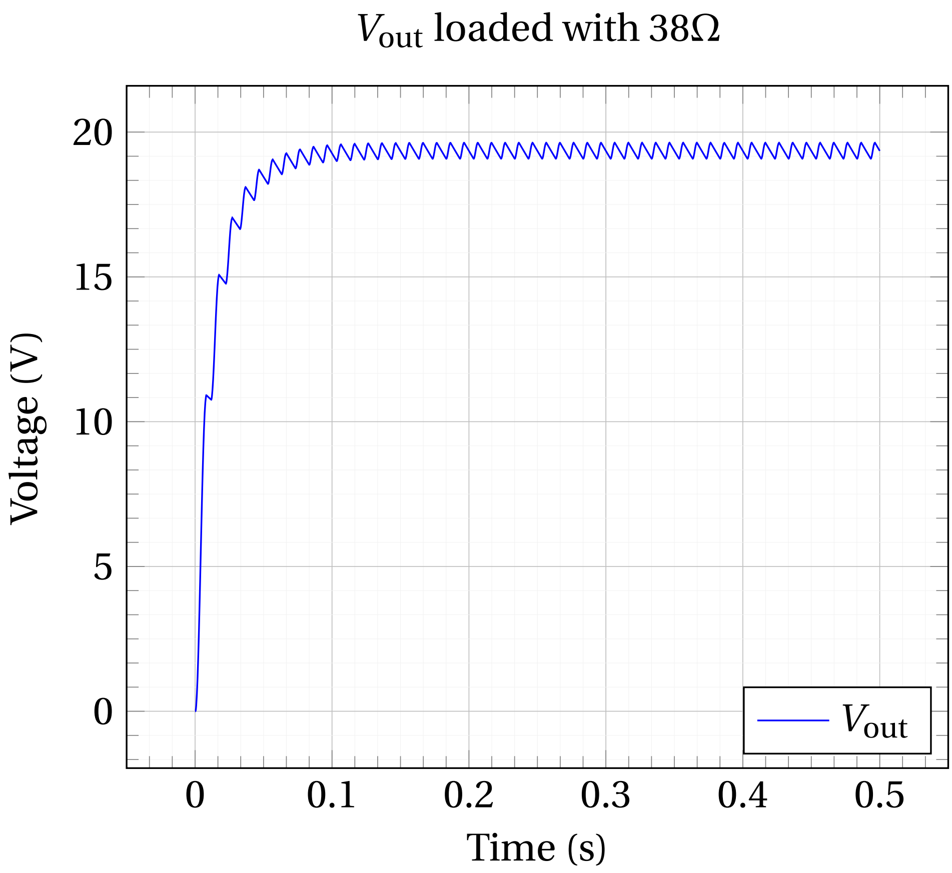

Figure A.2: The output voltage simulation waveform with the power supply loaded with a 38 Ω resistor.

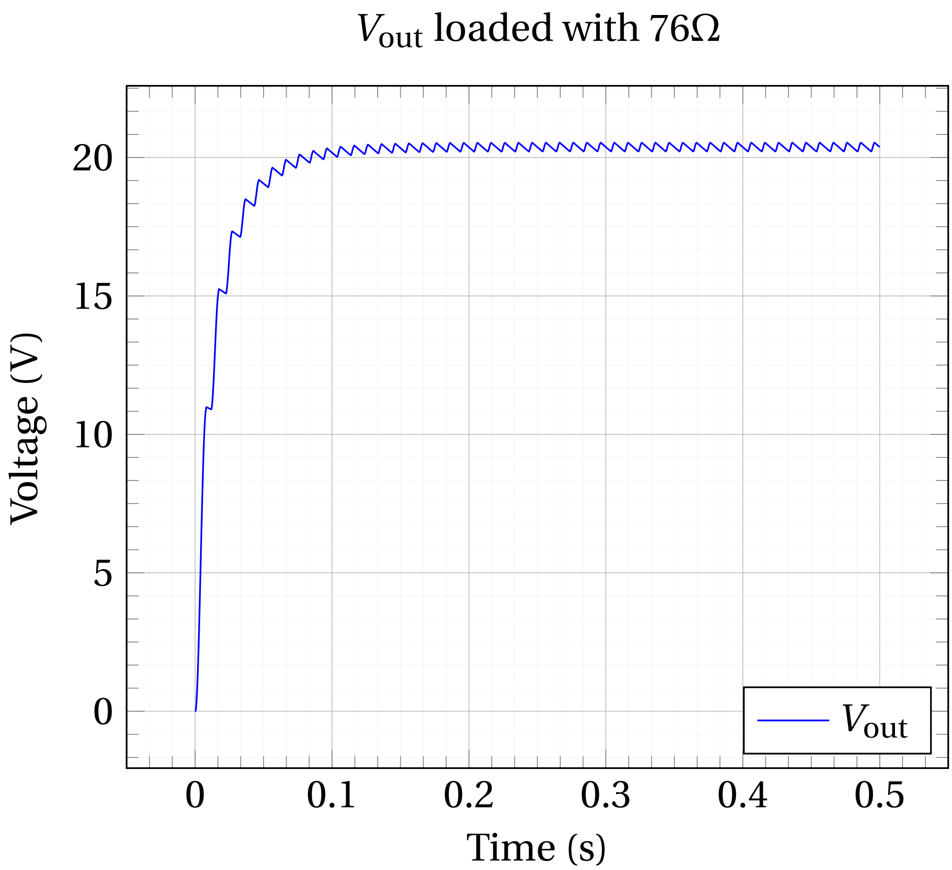

Figure A.3: The output voltage simulation waveform with the power supply loaded with a 76 Ω resistor.

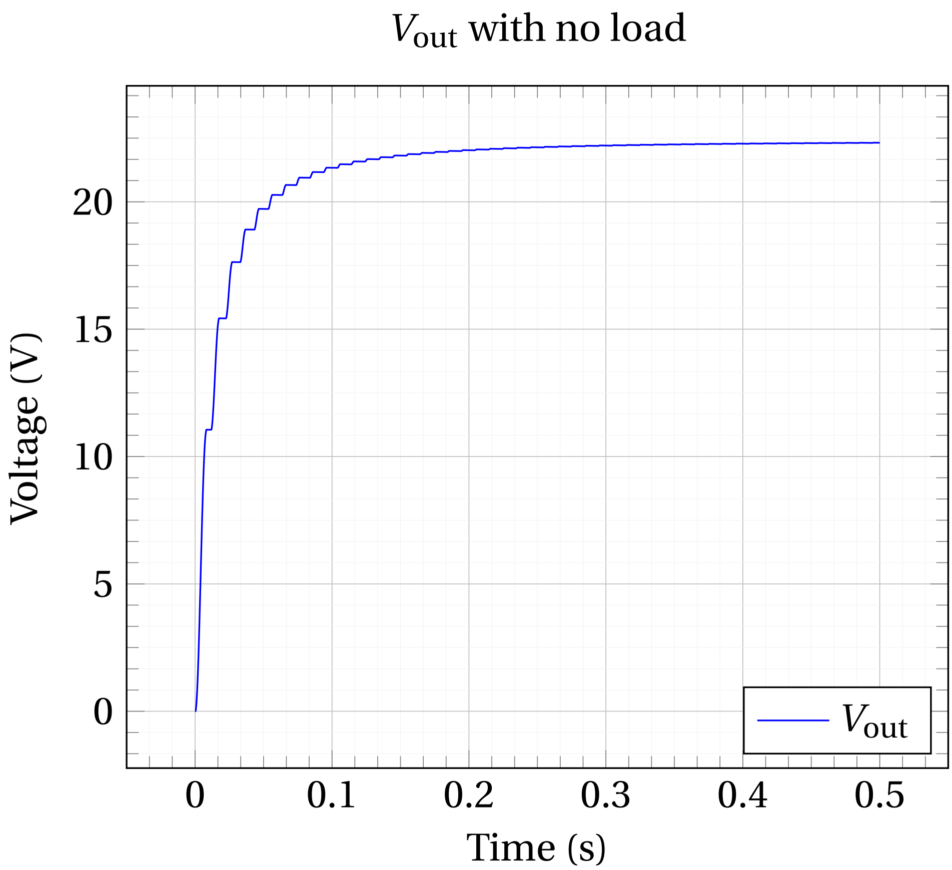

Figure A.4: The output voltage waveform of the simulation with no load on the output terminals.

B
Measurements

B.1. Average Voltage and Ripple Measurement Results

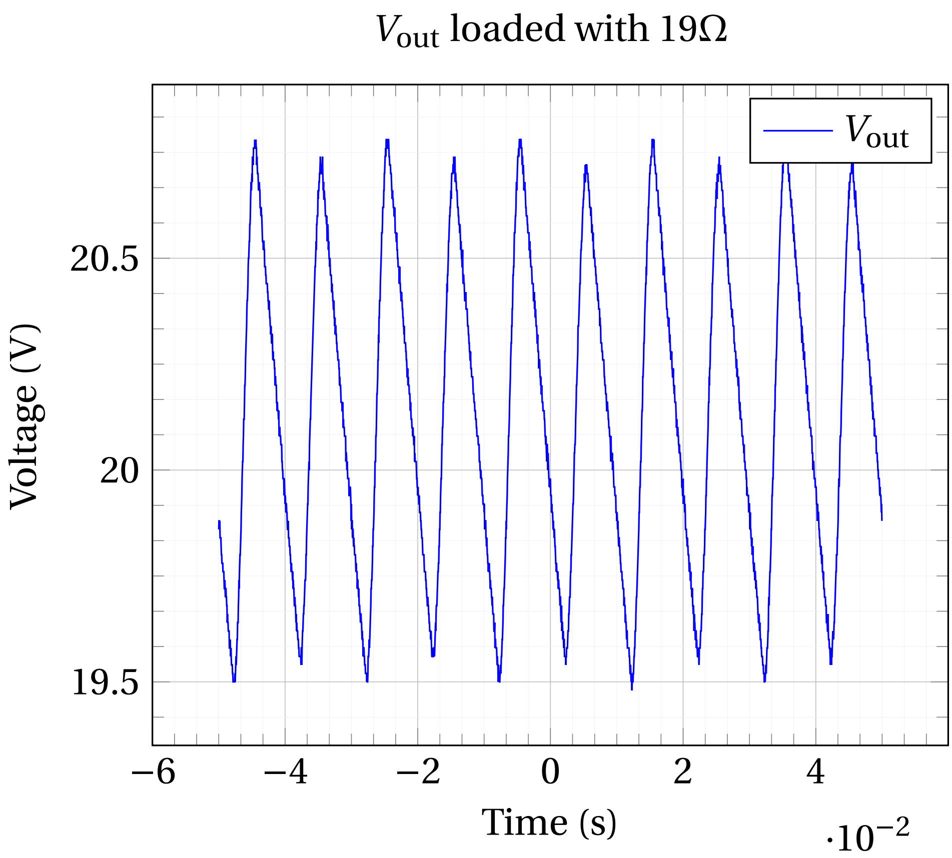

Figure B.1: The output voltage waveform with the power supply loaded with a 19 Ω resistor.

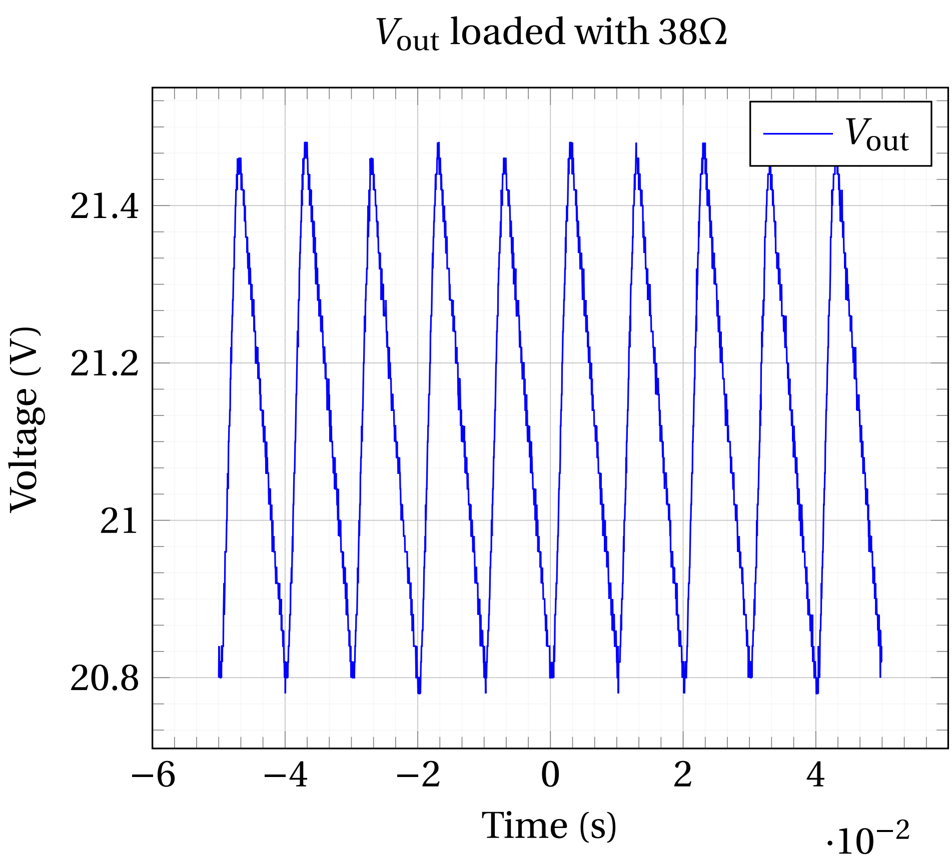

Figure B.2: The output voltage waveform with the power supply loaded with a 38 Ω resistor.

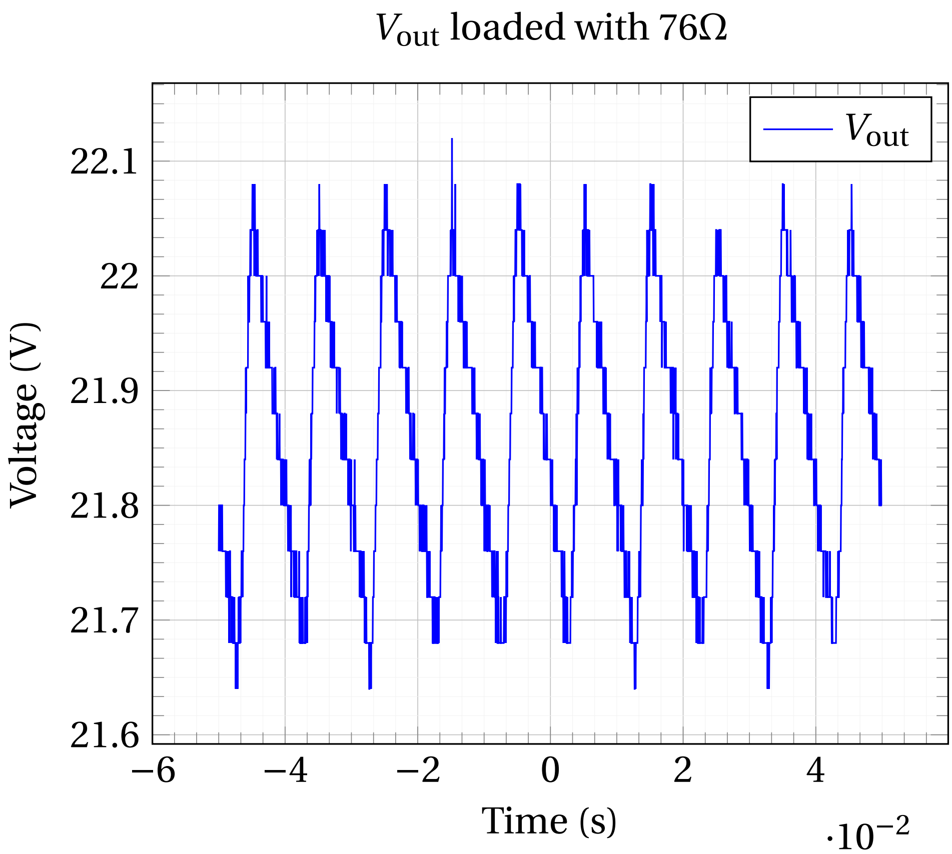

Figure B.3: The output voltage waveform with the power supply loaded with a 76 Ω resistor.

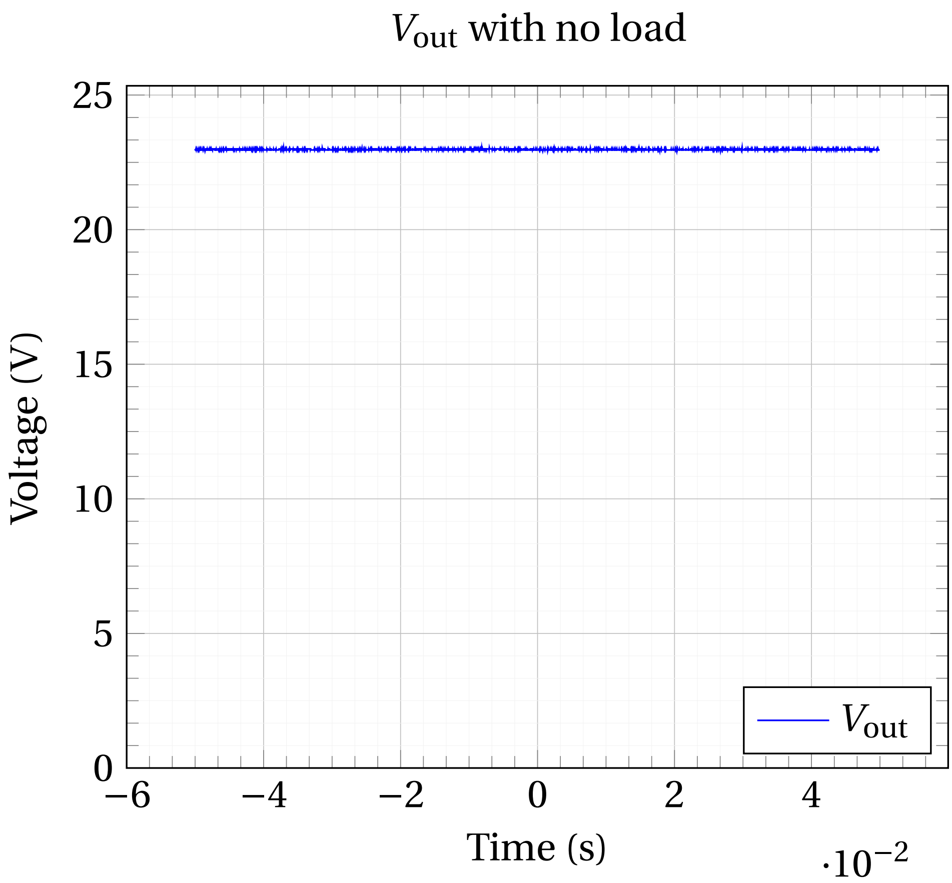

Figure B.4: The output voltage waveform with no load on the output terminals.

B.2. Symmetry of Power Supply

To show that the claim that the negative part of the power supply is the mirrored counterpart of the positive part also holds in practice, some measurements were conducted. In figure B.5, a 38Ω resistor was connected between the positive output and ground and the negative output and ground. This figure shows that the positive output mirrored around 0 V equals the negative output. Figure B.6 shows this too.

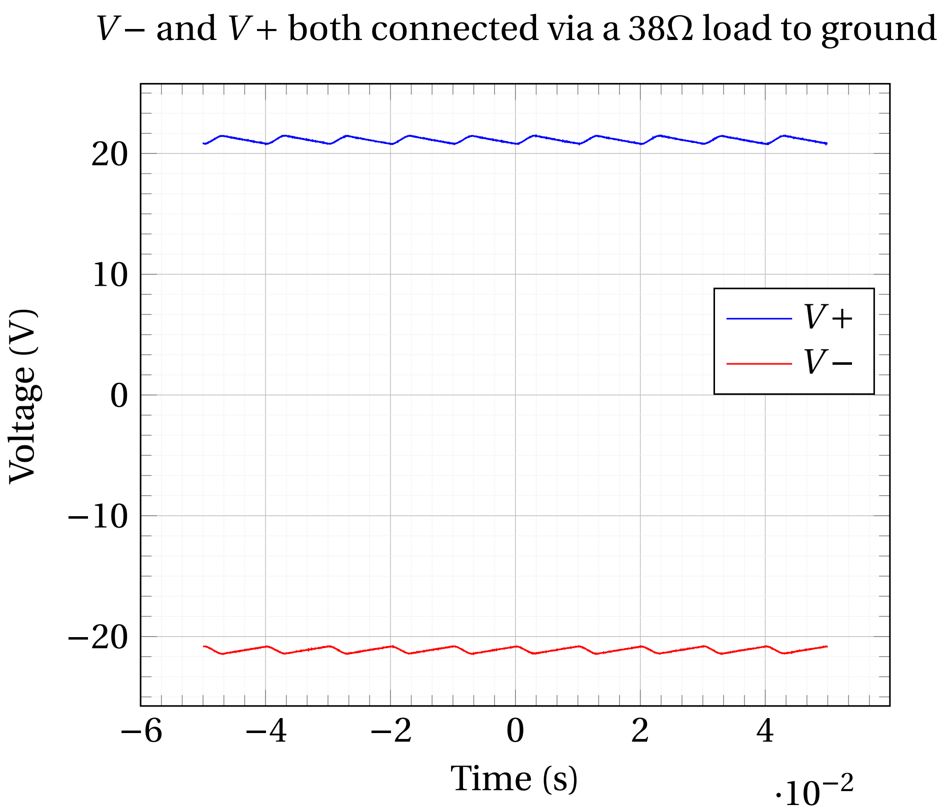

Figure B.5: The output voltage waveform with the power supply loaded with a 38 Ω resistor.

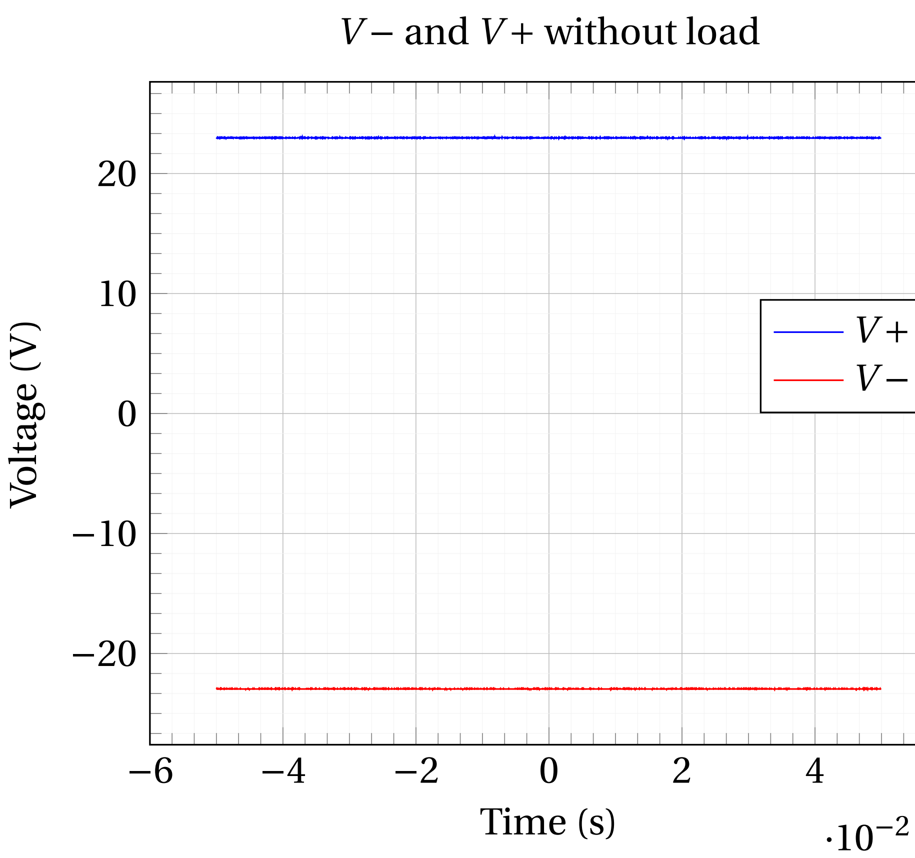

Figure B.6: The output voltage waveform with the power supply under no load.

C

Code

C.1. Ripple and Average Voltage Simulations

Below code was used to calculate the average voltage and ripple of the output voltage of the simulations.

```
import pandas as pd

def ripple(avg, max):
    return (max-avg)/avg*100


datas = [(”.\\19 ohm.txt”,19),
      (”.\\38 ohm.txt”,38),
      (”.\\76 ohm.txt”,76),
      (”.\\no load.txt”,None)]

for data in datas:
    file = data[0]
    resistance = data[1]

    data = pd.read_csv(file, delimiter=”\t”)
    #Only take the last part of the simulation to avoid the waveform when the capacitors are
        still being loaded
    t = data[”time”][len(data[”time”])//3*2:]
    v = data[”V(n001)”][len(data[”V(n001)”])//3*2:]
    i = data[”I(R2)”][len(data[”I(R2)”])//3*2:]

    maxV = v.max()
    minV = v.min()
    avgV = (maxV + minV)/2
    meanI = i.mean()

    if resistance == None:
        print(f”Using {file} (Power supply is not loaded)”)
    else:
        print(f”Using {file} (Power supply is loaded with a {resistance} Ohm resistor)”)

    print(f”    Load resistance: {resistance}”)
    print(f”    Average Voltage: {avgV:.3}V”)
    print(f”    Average Current: {meanI:.3}A”)
    print(f”    Ripple: {ripple(avgV, maxV):.3}%”)
```

C.2. Ripple and Average Voltage Measurements

Below code was used to calculate the average voltage and ripple of the output voltage of the measurements.

```
import pandas as pd

def ripple(avg, max):
    return (max-avg)/avg*100

# Tuples are formatted as (filename,resistance)
datas = [(".\\19 ohm\\F0009CH1.CSV",19),
      (".\\38 ohm\\F0007CH1.CSV",38),
      (".\\76 ohm\\F0011CH1.CSV",76),
      (".\\No load\\F0008CH1.CSV",None)]

for data in datas:
    file = data[0]
    resistance = data[1]

    measured_data = pd.read_csv(file, usecols=[3,4])
    t = measured_data["d"]
    v = measured_data["e"]

    maxV = v.max()
    minV = v.min()
    avgV = (maxV + minV)/2

    if resistance == None:
        print(f"Using {file} (Power supply is not loaded)")
    else:
        print(f"Using {file} (Power supply is loaded with a {resistance} Ohm resistor)")
    print(f"    Load resistance: {resistance}")
    print(f"    Average Voltage: {avgV:.3}V")
    if resistance == None:
        print(f"    Average Current: 0.00A")
    else:
        print(f"    Average Current: {avgV/resistance:.3}A")
    print(f"    Ripple: {ripple(avgV, maxV):.3}%")
```