



UNIVERSITY OF NAIROBI

FACULTY OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

**DESIGN OF A 100W POWER AMPLIFIER WITH DARLINGTON
COMPLEMENTARY SYMMETRY OUTPUT POWER TRANSISTOR**

PROJECT INDEX: 113

SUBMITTED BY: KOLL JACKSON RISONA

F17/37338/2010

SUPERVISOR: MR. S. L OGABA

EXAMINER: PROF ABUNGU

PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE AWARD OF THE DEGREE OF
BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING
OF THE UNIVERSITY OF NAIROBI

2016

DECLARATION OF ORIGINALITY

I, KOLL JACKSON RISONA (F17/37338/2010), hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

.....
Name of student

.....
Date

This project has been submitted for examination with my approval as university supervisor.

.....
Name of supervisor

.....
Date

DEDICATION

I dedicate this project to my parents Mr. and Mrs. John Kol ole Sawi, my siblings and friends for their continued and undying support throughout this journey and I am forever grateful for the opportunity they have given me to achieve my dreams.

ACKNOWLEDGEMENT

I would like to express my gratitude towards my project supervisor Mr. S.L. Ogaba of The Nairobi University and my colleagues for their guidance and constant supervision as well as providing necessary information regarding the project and also for their support in completing the project.

I am also grateful to electronics lab technicians for giving me permission to use their facilities.

ABSTRACT

An amplifier is an electronic device used to magnify the value of a signal. It works by increasing the energy output from an input signal by enlarging the amplitude.

Amplifiers fall into a number of classification groups. These are placed into classes that are tailored for outputs of audio. The basic design of an amplifier is such that it can strengthen the overall signal thus giving a stronger audio output. Amplifiers have a number of instrumental properties, such as bandwidth, noise, gain, linearity, efficiency and output dynamic range. These figures of merit give the specifications of an amplifier thus determine its properties when it comes to the power input and outputs that govern its operation.

There are different types of amplifiers. These include current, voltage, power, operational transistor among others. This project mainly focuses with power amplifiers, which are mainly used for audio system designs. The power amplifiers are having characteristics that determine the amount of power received and the output of the circuit. The power amplifiers thus give a high output level that can be applied to speaker systems from low power inputs. The primary focus for the audio power amplifiers used in the project would be on frequency response, gain, noise and distortion. The design process devises, tested and simulated various schemes to determine the best setup. This process was done to fully grasp the concepts and applications of audio power amplifiers and its applications.

Table of Contents

Contents

DECLARATION OF ORIGINALITY	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT.....	v
Table of Contents.....	vi
LIST OF TABLES.....	ix
LIST OF FIGURES	x
ABBREVIATIONS	xi
CHAPTER 1: INTRODUCTION	1
Power Amplifier.....	1
Problem statement.....	1
Significance.....	1
Project objective.....	2
Scope.....	2
CHAPTER 2: LITERATURE REVIEW	3
AMPLIFIERS	3
Amplifier Gain	3
Input Resistance	4
Output Resistance	5
POWER AMPLIFIER	5
POWER OUTPUT TRANSISTORS	9
DARLINGTON COMPLEMENTARY	9
AUDIO CROSSOVER NETWORK	10
PASSIVE FILTERS.....	11
ACTIVE FILTERS	11
Types of Active Filters.....	12
Butterworth Filter:	13
Chebyshev Filter.....	13
Bessel Filter	14
Elliptic Filter	14
SWITCHED-CAPACITOR FILTER	15

CHAPTER 3: DESIGN.....	16
POWER AMPLIFIER	16
Darlington Output Stage	17
Voltage Amplification stage	20
Driver Transistor.....	20
Bias Spreader	21
INPUT STAGE.....	22
Short Circuit Protector	24
ACTIVE FILTER	25
Sallen-Key Topology	25
Power Supply	29
CIRCUIT COMPONENTS	31
Resistors.....	31
Diodes	32
Capacitors	32
Transistors.....	33
Heat sinks.....	33
POWER AMPLIFIER PERFORMANCE SPECIFICATION.....	34
Distortion	34
Clipping.....	34
Frequency response.....	35
Output Current	35
Rated Output Power.....	35
Slew rate.....	36
CHAPTER 4: RESULTS AND SIMULATIONS	36
Circuit Diagram	36
Circuit Calculations	37
Computer Simulation Results	38
Results.....	39
Simulation.....	39
Laboratory Implementation.....	39
FILTER DESIGN SIMULATION RESULTS	40
LOW-PASS FILTER.....	41
BAND-PASS FILTER.....	41

HIGH-PASS FILTER	42
3-WAY FILTER FREQUENCY RESPONSE	43
CHAPTER 5	45
5.1 DISCUSSION	45
5.2 CONCLUSION.....	45
5.3 RECOMMENDATION	47
REFERENCES	48
APPENDICES	49

LIST OF TABLES

Table 2 current source results	22
Table 3 Resistor color bands.....	31
Table 4 Power Amplifier simulation results	39
Table 5 Output Power simulation	39
Table 6 Laboratory results	39
Table 7 POWER AMPLIFIER FREQUENCY RESPONSE.....	40
Table 8 Low Pass Filter	41
Table 9 Low Pass Filter	41
Table 10 Band Pass Filter	42
Table 11 High Pass Filter Freuency Response.....	43

LIST OF FIGURES

Figure 1 Amplifier Gain.....	3
Figure 2 Class A Amplifier.....	7
Figure 3 Class B amplifier Waveforms.....	8
Figure 4 Darlington Complementary	10
Figure 5 Frequency Response curve	12
Figure 6 Chebyshev and Butterworth frequency response	13
Figure 7 Bessel Filter frequency response	14
Figure 8 Power Amplifier stages	16
Figure 9 Darlington Complementary Output Stage	18
Figure 10 VAS stage.....	20
Figure 11 Current Source.....	21
Figure 12 Input Stage.....	23
Figure 13 Short Circuit Protector.....	25
Figure 14 Low Pass Filter	26
Figure 15 High Pass Filter	27
Figure 16 Band Pass Filter.....	28
Figure 17 Power Supply.....	30
Figure 18 Characteristic curve	32
Figure 19 Power Amplifier Frequency response	35
Figure 20 100w Power Amplifier	36
Figure 21 Amplifier Simulated Waveform	39
Figure 22 Laboratory Waveform	40
Figure 23 Band Pass Filter Frequency Response.....	42
Figure 24 High Pass Filter Frequency Response	43
Figure 25 3-way Active filter frequency response.....	44
Figure 26 circuit PCB layout	49
Figure 27 Circuit Design.....	50

ABBREVIATIONS

Hz= Hertz

dB = Decibel

KHz =Kilo Hertz

μ = micro

m = milli

H = Henries

F = Farads

Ω = Ohms

Π = 3.14

R = Resistance

L= Inductance

C = Capacitance

Z_o = Impedance

f_c = Cross over frequency/ Cut off frequency

V= Voltage

P = Power

f = frequency

LPF = Low pass filter

HPF = High pass filter

BPF = Band pass filter

F_L = Lower cut off frequency

F_H = Upper cut off frequency

W= Watts

Rms = root mean square.

CHAPTER 1: INTRODUCTION

Power Amplifier

An amplifier, electronic amplifier or amp is an electronic device that can increase the power of a signal. It amplifies an audio signal with low power so that it can be used to drive a loudspeaker. Power amplifiers are required for applications where high current switching currents are needed, such as driving a motor or feed a loudspeaker. As they are called, power amplifiers are used to deliver power to the load.

Amplifiers are used in wireless communications and broadcasting, and in audio equipment of all kinds. They are categorized as either weak-signal amplifiers or power amplifiers.

The first audio power amplifier was made in 1906 by Lee De Forest and came in the form of the triode vacuum tube. This particular mechanism evolved from the Audion, which was developed by De Forest. Unlike the triode which had three elements, the Audion only had two and did not amplify sound. Later on during the same year, the triode, a device with the capability of adjusting the movement of electrons from a filament to a plate and thus modulating sound was invented. It was vital in the invention of the first AM radio. Since then, the advancement in the electronics industry has seen numerous improvements of amplifier designs such as the invention of vacuum tubes after the world war two and the invention of silicon transistors in the 1970's which replaced almost all amplifiers because they were smaller and thus more efficient while also better at reducing distortion levels and cheaper to make.

Problem statement

The best amplifier systems effectively produce the required amplification without damage to the loudspeaker being driven by it and also they are able to operate in the whole frequency range audible to the human ear. Most modern music systems have separate speakers (woofer, mid-range & tweeter) connected to output of amplifiers. This project is employs the design of a power amplifiers with a short circuit protection and three way active filter network.

Significance

With constant evolution in technologically, power amplifiers have become more sophisticated and small in size. They can also produce more power and better music quality than previously designed power amplifiers. Improved technology has led to expensive power

amplifiers. This study is aimed at showing and providing alternative and affordable way of having a high quality power amplifier through the design of a 100W power amplifier with a 3-way active filter to enable the amplifier cover the whole range of frequencies i.e., base, tweeter and midrange. This is achieved by using locally available and affordable components to achieve the same high quality audibility.

Project objective

The main objective in this project is to design and build a power amplifier that will amplify signals up to 100 watts in the range of 20Hz to 20 kHz. This will be achieved by

- i. Choosing a cheaper and less bulky circuitry that can produce frequencies in the required range
- ii. Design a power amplifier with a Darlington complementary output transistor
- iii. To design a preamplifier that will help boost the signal to level required for input signal of the power amplifier
- iv. To design an active filter that will enable a 3way output for different signal frequencies i.e., low pass, band pass and high pass
- v. Test the complete power amplifier built and verify it works.

Scope

The project will entail building a power amplifier that could amplify sound signals to frequencies suitable for human ear (around 20 kHz) with a total output power of 100 watts divided into three outputs each of a different frequency. It will involve the hardware design of a preamplifier, an active crossover filter to divide the frequencies and a power amplifier to amplify the signal that will produce good musical signals in a 3way output to enhance and make the sound signal for clear and undistorted.

CHAPTER 2: LITERATURE REVIEW

AMPLIFIERS

Amplifier circuits form the basis of most electronic systems many of which need to produce high power to drive some output device. An amplifier is an electronic device that can increase the power of a signal. It does this by taking energy from a power supply and controlling the output to match the input signal shape but with the larger amplitude. In this sense, an amplifier modulates the output of the power supply. There are many forms of electronic circuits classed as amplifiers, from Operational Amplifiers and Small Signal Amplifiers up to Large Signal and Power Amplifiers with the classification of an amplifier depending upon the size of the signal, its configuration, class and application. In general, all ideal signal amplifiers have three main properties;

- Input resistance (R_{IN})
- Output resistance (R_{OUT})
- Amplifier gain (A)

With the above properties, all classes of amplifiers can be analyzed to show the relationship between these properties.

Amplifier Gain

Amplifier gain is the relationship that exists between the signals measured at the output with the signal measured at the input. It is simply the ratio of the output divided by the input.

There are three different kinds of amplifier gain which can be measured and these are: Voltage Gain (A_v), Current Gain (A_i) and Power Gain (A_p). It depends upon the quantity being measured as shown below.

Amplifier Gain of the Input Signal

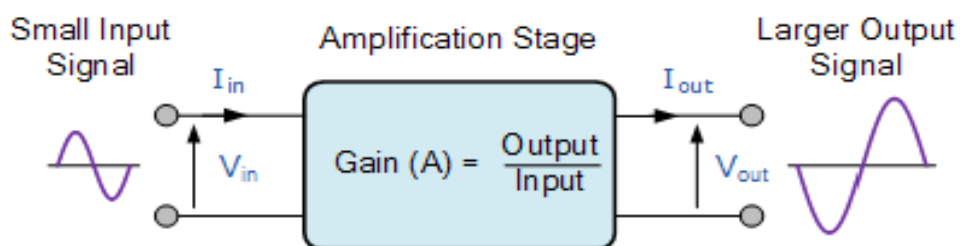


Figure 1 Amplifier Gain

Voltage Amplifier Gain

$$\text{Voltage Gain } (A_v) = \frac{\text{output voltage}}{\text{input voltage}} = \frac{V_{out}}{V_{in}}$$

Current Amplifier Gain

$$\text{Current Gain } (A_i) = \frac{\text{output current}}{\text{input current}} = \frac{I_{out}}{I_{in}}$$

Power Amplifier Gain

$$\text{Power Gain } (A_p) = A_v * A_i$$

Note that for the Power Gain you can also divide the power obtained at the output with the power obtained at the input and when calculating the gain of an amplifier, the subscripts v, i and p are used to denote the type of signal gain being used.

The power Gain or power level of the amplifier can also be expressed in Decibels, (dB). The Bel (B) is a logarithmic unit (base 10) of measurement that has no units. Since the Bel is too large a unit of measure, it is prefixed with deci making it Decibels instead with one decibel being one tenth (1/10th) of a Bel. To calculate the gain of the amplifier in Decibels or dB, we can use the following expressions.

- Voltage Gain in dB: $a_v = 20 \log A_v$
- Current Gain in dB: $a_i = 20 \log A_i$
- Power Gain in dB: $a_p = 10 \log A_p$

A positive value of dB represents a Gain and a negative value of dB represents a Loss within the amplifier. The -3dB point of an amplifier is called the half-power point which is -3dB down from maximum, taking 0dB as the maximum output value.

Input Resistance

Input Impedance, Z_{in} or Input Resistance is an important parameter in the design of a transistor amplifier and as such allows amplifiers to be characterized according to their

effective input and output impedances as well as their power and current ratings. An amplifier's impedance value is particularly important for analysis especially when cascading individual amplifier stages together one after another to minimize distortion of the signal.

The input impedance of an amplifier is the input impedance seen by the source driving the input of the amplifier. If it is too low, it can have an adverse loading effect on the previous stage and possibly affecting the frequency response and output signal level of that stage. But in most applications, common emitter and common collector amplifier circuits generally have high input impedances.

Some types of Amplifier Designs, such as the common collector amplifier circuit automatically have high input impedance and low output impedance by the very nature of their design. Amplifiers can have high input impedance, low output impedance, and virtually any arbitrary gain, but where an amplifier's input impedance is lower than desired, the output impedance of the previous stage can be adjusted to compensate or if this is not possible then buffer amplifier stages may be needed.

Output Resistance

Every electricity supplying component has output impedance and so does power amplifiers. You could look at it as a resistor in series with the output of the amplifier, representing the imperfection of that amplifier's output stage. The output impedance is related to the damping factor. Damping factor is the measure for the control an amplifier has over a speaker cabinet. A high damping factor coincides with low output impedance which is good for the power amplifier. Damping factor is calculated as follows;

$$\text{Damping factor} = \frac{\text{load impedance}}{\text{output impedance}}$$

This shows why it is important for loudspeaker cables should be made of large diameter copper wires to ensure the damping factor is not lowered.

POWER AMPLIFIER

This is an amplifier which produces amplification of power between the input and output. It is an electronic amplifier that amplifies low-power signals composed primarily of frequencies between 20 and 20,000 Hz, which is the human range of hearing, to a level suitable for

driving loudspeakers. Power amplifiers are required for applications where high current switching currents are needed, such as driving a motor or feed a loudspeaker. As they are called, power amplifiers are used to deliver power to the load and as we know power is the product of current and voltage. Therefore, the power delivered to the load is the product of voltage and current supplied. In a practical amplifier, there are several stages that amplify a weak signal until sufficient power is available to operate a loudspeaker or other output devices. The first stages perform the function of power amplification and only the last stage is designed to provide maximum power. The final stage is known as the power stage. A power amplifier does not amplify power but it actually draws power from DC supply connected to the output circuit and converts it into AC signal power useful for the load of the power amplifier. This conversion from DC power supply input to the AC voltage signal output forms the basic principle of the power amplifier thus a power amplifier may also be defined as a device that converts DC power to AC signal power. This AC power at the output is controlled by the input signal. Although the amplification is high, the efficiency of the conversion is poor.

$$\text{amplifier efficiency} = \frac{\text{power delivered to the load}}{\text{dcpower taken from supply}} = \frac{P_{out}}{P_{in}}$$

CLASSIFICATION OF POWER AMPLIFIERS

- Audio power Amplifiers

They are known as small signal power amplifiers and they raise the power levels of signals that have audio-frequency range i.e., 20Hz up to 20 kHz.

- Radio-power amplifiers

Also known as large signal power amplifiers and they raise the power level of signals that have radio frequency range. They amplify a specific frequency or narrow band of frequencies while rejecting all other frequencies.

CLASSIFICATION ACCORDING TO MODE OF OPERATION

The classification is based on the amount of transistor bias and amplitude of the input signal.

CLASS A POWER AMPLIFIER

A class A amplifier is equivalent to a current source. This is because, as it operates in the linear portion of its characteristic curve, the single output device conducts through a full 360° of the output waveform. To achieve high linearity and gain, the output stage of the amplifier is biased “ON” at all times. In this case, the transistor is so biased that the output current flows for the entire cycle of the input signal making the output waveform similar to the input waveform. This class of amplifier is mainly used in applications when a distortion less setup is required and also used for amplifying signals of small amplitude.

Class A Amplifier

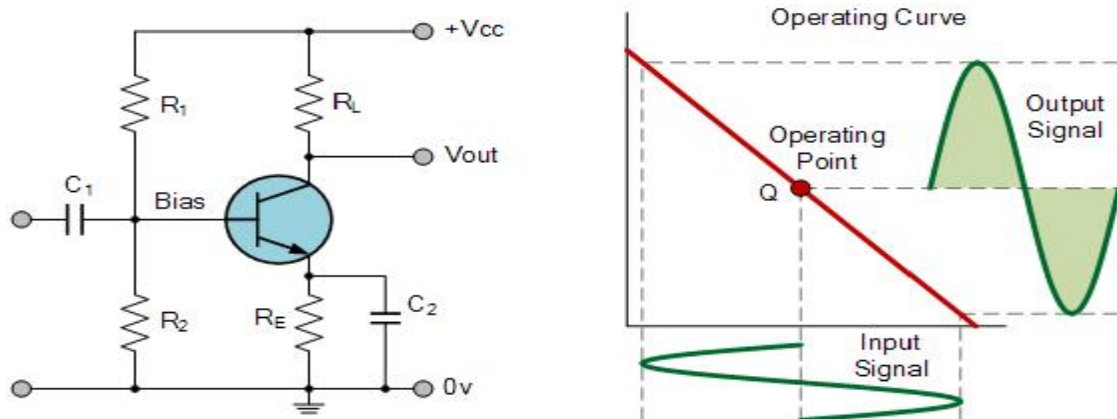


Figure 2 Class A Amplifier

CLASS B POWER AMPLIFIER

A basic class B amplifier uses two complementary transistors either bipolar junction transistor (BJT) or field effect transistor (FET) for each half of the waveform with its output stage configured in a ‘push-pull’ arrangement, so that each transistor device amplifies only half of the output waveform. Class B amplifiers were invented as a solution to the efficiency and heating problems of class A amplifiers. In the operation of this amplifiers, there is no direct dc bias current like in class A as its quiescent current is zero so that the dc power is small and therefore its efficiency is higher compared to class A. This means that class B amplifier does not require a biasing system and the operating point is selected at the collector cutoff voltage because of the total absence of negative half cycle from the output resulting in high distortion. At zero input, there is zero output and these results in only half the input signal being present at the amplifier output giving a greater amount of amplifier efficiency. The zero input signal represents the best condition for class B amplifiers because of zero collectors current though the transistor dissipates more power with increase in signal strength.

Class B Output Waveform

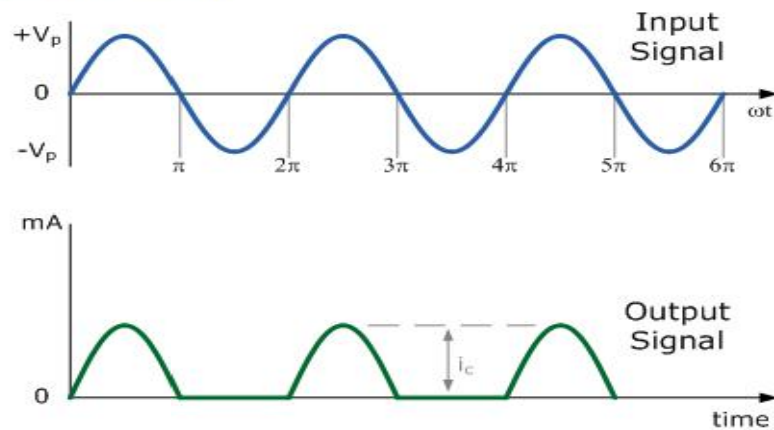


Figure 3 Class B amplifier Waveforms

ADVANTAGES OF CLASS B POWER AMPLIFIER

- Have high amplifier efficiency
- Compared to class A, they experience less power dissipation
- They can be used for more powerful outputs compared to class A
- For ideal cases, they have no DC components in the output for ideal cases

DISADVANTAGES OF CLASS B AMPLIFIERS

- Creates crossover distortion
- Supply current changes with signal, hence it requires stabilized supply

CLASS AB POWER AMPLIFIERS

Class AB combines the good points of class A and class B amplifiers. This class of amplifiers is probably the most common amplifier class currently used in home stereo because of their improved efficiency brought about by class B advantages and a distortion performance that is closer to that of a Class A amplifier. An amplifier may be biased at a dc level above the zero base current level of class B power amplifiers and above one-half the supply voltage level of class A; this bias condition is class AB. Class AB operation still needs a push-pull connection to achieve a full output cycle, but the dc bias level is usually closer to zero base current level for better power efficiency. For class AB operation the output signal swing occurs between 180 degree and 360 degree and is neither class A nor class B operation.

POWER OUTPUT TRANSISTORS

There are many reasons that designers need very high gain transistors, and although they are available in a single package, it is generally better to build your own using discrete devices. This gives much greater flexibility, and allows you to create configurations that are optimised for the specific task required.

In many power amplifiers the op-amp circuit is constructed with discrete components specifically designed for higher rail Voltages. To create a high gain transistor, it is a matter of connecting two or more transistors such that the collector current of the first is amplified by the second. Output transistors are added to provide extra current to drive a speaker. Large output transistors only have a small HFE current gain; therefore driver transistors are placed in front of the output transistors to increase the total current gain. The bias string can now be placed in the Class A driver circuit. Output transistors can be arranged in three different ways;

- Darlington Complementary
- Quasi Complementary
- Compound Complementary

DARLINGTON COMPLEMENTARY

Also known as the Darlington pair consists of two bipolar transistors that are connected in order to provide a very high current gain from a low base current. In a Darlington transistor, the input transistors emitter is wired to the output transistors base and their collectors are tied together. Therefore the current that is amplified by the input transistor is amplified further by the output transistor.

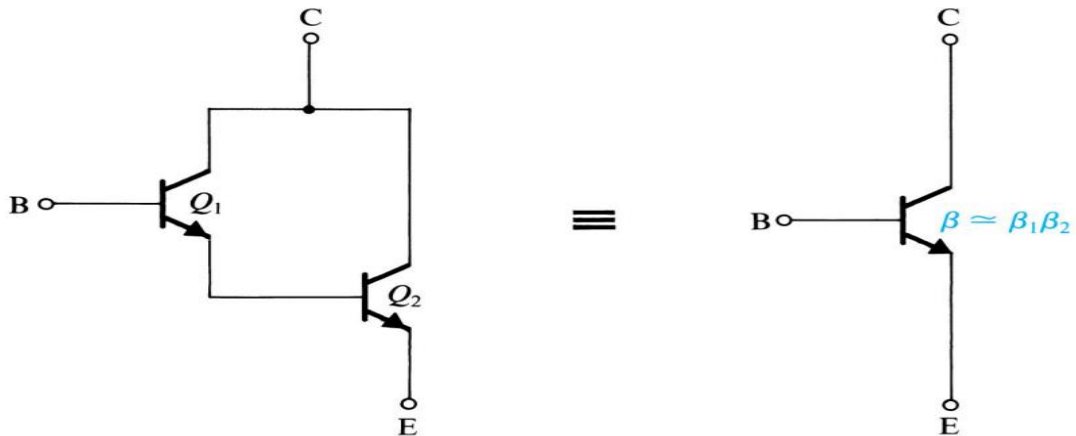


Figure 4 Darlington Complementary

APPLICATIONS OF DARLINGTON TRANSISTORS

They are used in applications where a high gain is needed at a low frequency while photo-Darlington are used in light sensitive circuits. Some applications include:

- Power regulators
- Audio amplifier output stage
- Display drivers
- Motor controllers
- Touch and light sensors
- Solenoid control

ADVANTAGES OF DARLINGTON PAIR

- Have very high current gain
- Have very high input impedance for the overall circuit
- Darlington pairs are widely available in a single package hence offer a convenient and easy circuit configuration to use

DISADVANTAGES OF THE DARLINGTON PAIR

- They have slow switching speeds
- Have limited bandwidth
- Higher overall base-emitter voltage of $2V_{be}$
- High saturation voltage which can lead to high levels of power dissipation

AUDIO CROSSOVER NETWORK

Almost all individual loudspeaker drivers cannot cover the entire audio spectrum from low frequencies to high frequencies with acceptable relative volume and lack of distortion hence most hi-fi speaker systems use a combination of several loudspeaker drivers for each

frequency band. With optimized loudspeakers for each band, crossover networks split the audio signal into separate frequency bands that can be separately routed to the optimized loudspeaker using filters.

Classifications of crossovers;

- Passive filters and active filters
- Analog and digital
- Discrete time and continuous time
- Linear and non-linear
- Infinite impulse response (IIR) and finite impulse response (FIT)
- High pass, low pass, band pass, band reject, and all pass

PASSIVE FILTERS

This type of filter is made entirely of passive components. It is commonly arranged in a cauer topology to obtain a Butterworth filter. Passive implementations of linear filters are based on combinations of resistors (R) with reactive components such as inductors (L) and capacitors (C). In its network, capacitors allow high frequency signals and block low-frequency signals while inductors block high frequency signals and conduct low-frequency signals. A filter in which a signal passes through a capacitor provides a path to ground or in which signal passes through an inductor, presents less attenuation to low-frequency signals than high frequency signals and is therefore a low-pass filter. On the other hand, a high-pass filter, occurs if a signal passes through a capacitor or has a path to ground through an inductor, enabling the filter to present less attenuation to high-frequency signals than low-frequency signals.

Although resistors on their own have no frequency selective properties, they are used in circuits with inductors and capacitors to determine time-constants circuits and the frequencies to which they respond.

Very high performance active filter networks are likely to be more cheaper than passive filter networks due to individual components capable of good performance at high currents and voltages at which speaker systems driven are hard to make. Passive filter networks do not depend upon an external power supply.

ACTIVE FILTERS

These are usually amplifying elements, mostly op-amps, with resistors and capacitors in their feedback loops meant to synthesize the desired filter characteristics. The active filters can

have high-input impedance, low output impedance and virtually any amount of gain. They are easier to design than passive filters because they do not have inductors hence inductor effects and problems associated with them are reduced. Accuracy and value spacing are some of the problems but they also affect capacitors at a lesser degree compared to inductors. At high frequencies, performance is hindered by the gain bandwidth product of the amplifying elements but within the range of the amplifiers' operating frequency.

By use low tolerance resistors and capacitors, the op-amp active filter can achieve very good accuracy at the amplifiers' operating frequency range but due to the amplifying circuitry, active filters will generate noise which can be minimized by the use of low-noise amplifiers and careful circuit design.

There are basically 4 types of active filters. They are;

- Butterworth,
- Chebyshev,
- Bessel and
- Elliptic filters.

Types of Active Filters

Butterworth, Chebyshev, Bessel and Elliptic filters.

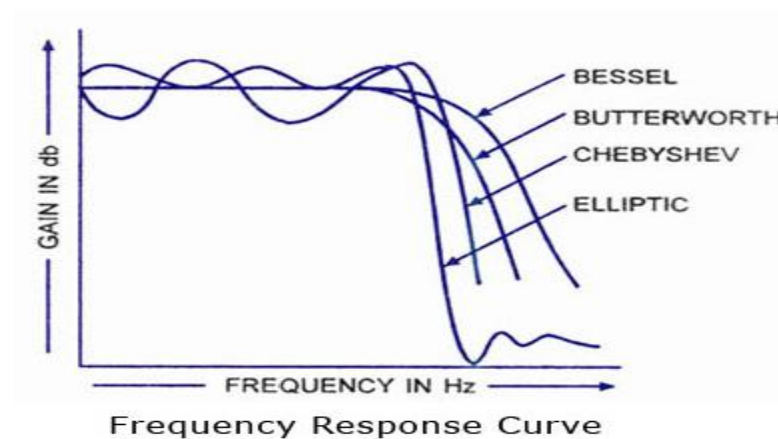


Figure 5 Frequency Response curve

Butterworth Filter:

This filter is also called as maximally flat filter. This class of filters approximates the ideal filter well in the pass band. Frequency response curves of different types of filters are shown in figure. The Butterworth filter has an essentially flat amplitude-frequency response up to the cut-off frequency. The sharpness of the cut-off can be seen in the figure. It is to be noted that all the three filters reach a roll-off slope of -40 dB per decade at frequencies much larger than cut-off. Although Butterworth filters achieve the sharpest attenuation, their phase-shift as a function of frequency is non-linear. It has a monotonic drop in gain with frequency in the cut-off region and a maximally flat response below cut-off frequency, as illustrated in figure. The Butterworth filter has characteristic somewhere between those of Chebyshev and Bessel filters. It has a moderate roll-off of the skirt and a slightly nonlinear phase responses.

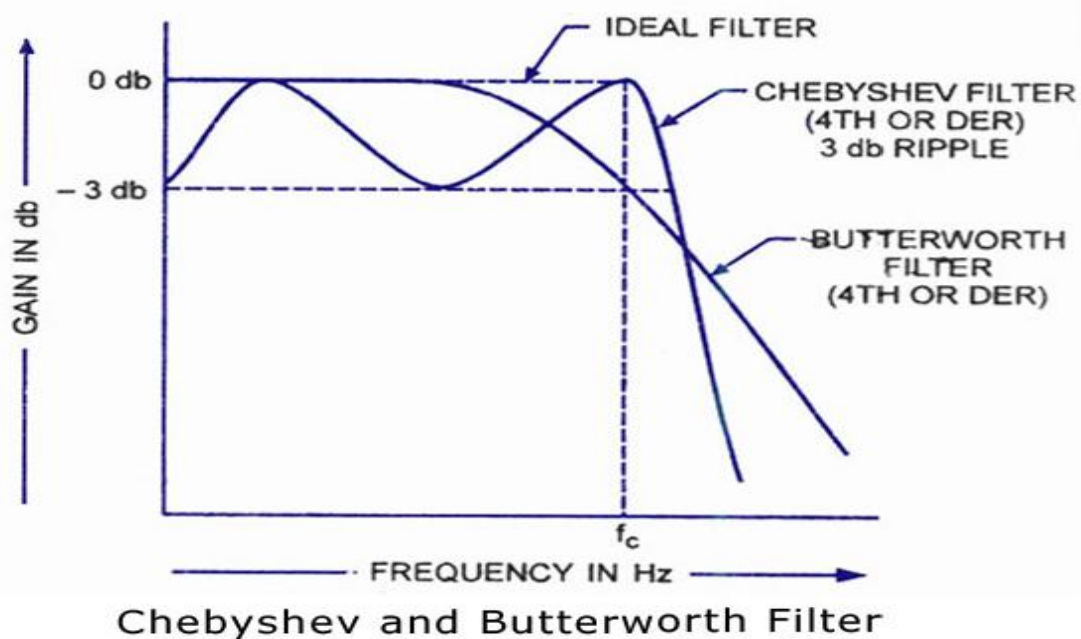


Figure 6 Chebyshev and Butterworth frequency response

Chebyshev Filter.

It is also called a equal ripple filter. It gives a sharper cut-off than Butterworth filter in the pass band. Both Butterworth and Chebyshev filters exhibit large phase shifts near the cut-off frequency. A drawback of the Chebyshev filter is the appearance of gain maxima and minima below the cut-off frequency. This gain ripple, expressed in db, is an adjustable parameter in filter design.

The faster the roll-off, the greater the peak-to-peak ripples in the pass band. The phase response is highly non-linear in the skirt region. Such unequal delays of data frequency in the pass band causes severe pulse distortion and thus increased errors at modern demodulators. This can be overcome somewhat by increasing the BW of the filter so that the phase region is extended. A Chebyshev filter is used where very sharp roll-off is required. However, this is achieved at the expense of a gain ripple in the lower frequency pass band.

Bessel Filter

The Bessel filter provides ideal phase characteristics with an approximately linear phase response up to nearly cut-off frequency. Though it has a very linear phase response but a fairly gentle skirt slope, as shown in figure. For applications where the phase characteristic is important, the Bessel filter is used. It is a minimal phase shift filter even though its cut-off characteristics are not very sharp. It is well suited for pulse applications.

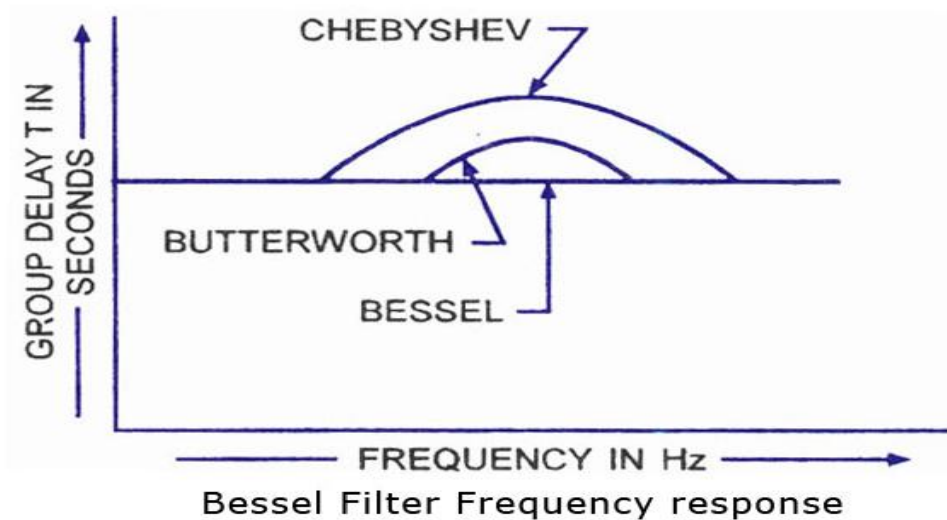


Figure 7 Bessel Filter frequency response

Elliptic Filter

This filter has the sharpest roll-off of all filters in the transition region but has ripples in both the pass band and stop band regions, as illustrated in figure. The elliptic filter can be designed to have very high attenuation for certain frequencies in the stop band, which reduces the attenuation for other frequencies in the stop band.

SWITCHED-CAPACITOR FILTER

This type of filter is widely available in monolithic form. The switched-capacitor filter solves some of the problems found in standard active filters and also increases the capabilities of filters. It needs no external capacitor or inductors and this filter is set to a typical accuracy of + or – 0.2% by an external clock frequency. Through changing the clock frequency, the cut-off frequencies of consistent, repeatable filter designs to be variable over a wide range and in addition, the switched capacitor filters can have low sensitivity to temperature changes. This type of filter is clocked and its input signal is sampled at a high rate then processed on a discrete-time instead of continuous-time like the conventional active and passive filters. Switched-Capacitor filters contain MOS switches and on-chip capacitors are closely matched to other capacitors on the IC hence integrated filters whose cutoff frequencies are proportional to, and determined only by external clock frequency

Advantages of switched-capacitor filter

- They can achieve high dynamic range since the signal does not require quantization
- They can be easily implemented on an integrated circuit
- They occupy a small chip area
- Their frequency characteristics can be changed easily by changing the clock speed

Disadvantages of switched-capacitor filters

- They produce more noise at the output
- They need a clock circuit and anti-aliasing filters
- They are not suited for high frequencies
- They experience sample data effect

CHAPTER 3: DESIGN

POWER AMPLIFIER

Due to the use of a 3-way active filter, each filter requires an amplifier and therefore three similar amplifiers were design. In theory, every amplifier produces some amount of power amplification, but in practical, every amplifier cannot be called a power amplifier. The amount of power amplification is the factor that makes an amplifier a power amplifier. A power amplifier must produce a considerable amount of power amplification to drive a load. In the process of designing a practical power amplifier, power is not the only factor that is considered, i.e. emphasis is given to the following factors;

- Performance
- Reliability
- Ruggedness

An audio power amplifier should have dedicated circuits for producing voltage gain and current gain.

A power amplifier is made up of three stages namely;

- i. Input stage
- ii. Voltage Amplification Stage
- iii. Output stage.



Figure 8 Power Amplifier stages

For many amplification purposes, a single transistor does not provide enough gain, so multiple circuits, or 'stages of amplification' are needed. When an amplifier contains multiple stages the total gain is the product of the individual stage gains:

$$\text{Gain } G = G_1 \times G_2 \times G_3$$

Or, when the gain is expressed in decibels, the sum of the individual stage gains is

$$\text{Total gain in dBs} = \text{dB}_1 + \text{dB}_2 + \text{dB}_3.$$

The way in which the individual stages are coupled together is important. The design of the coupling circuitry must fulfil several requirements, including:

- Impedance Matching.
- Correct Frequency Response.
- DC Isolation.

Output Transistor Matching

In the output stage transistors, the positive half-cycle and the negative half-cycle are supposed to have same behavior otherwise an even-order distortion will result. The signal in both the top and bottom transistors follows different paths depending on the direction of net current flow to the load.

Beta Matching

The difference in transistor gain will result to difference between positive and negative going signal. This difference in current gain of the upper and lower half of the output stage cause the load on the driver stage to be different on the negative and positive half-cycles of the signal current swing resulting second harmonic distortion.

Emitter and Base Resistance Matching

A base resistor provides the necessary resistance to bias the base junction of a bipolar junction transistor (BJT). The resistor “ R_b ” controls the amount of current “ I_b ” flowing into the base, which controls the amount of current flowing through the collector “ I_c ”. The value of this resistance is different for different input voltages.

Darlington Output Stage

This is the stage connected to the loudspeaker. It consists of two emitter followers one after the other. The output stage of a power amplifier produces a current gain that is a product of the betas of the driver and output transistors. This stage also produces unity gain approximately.

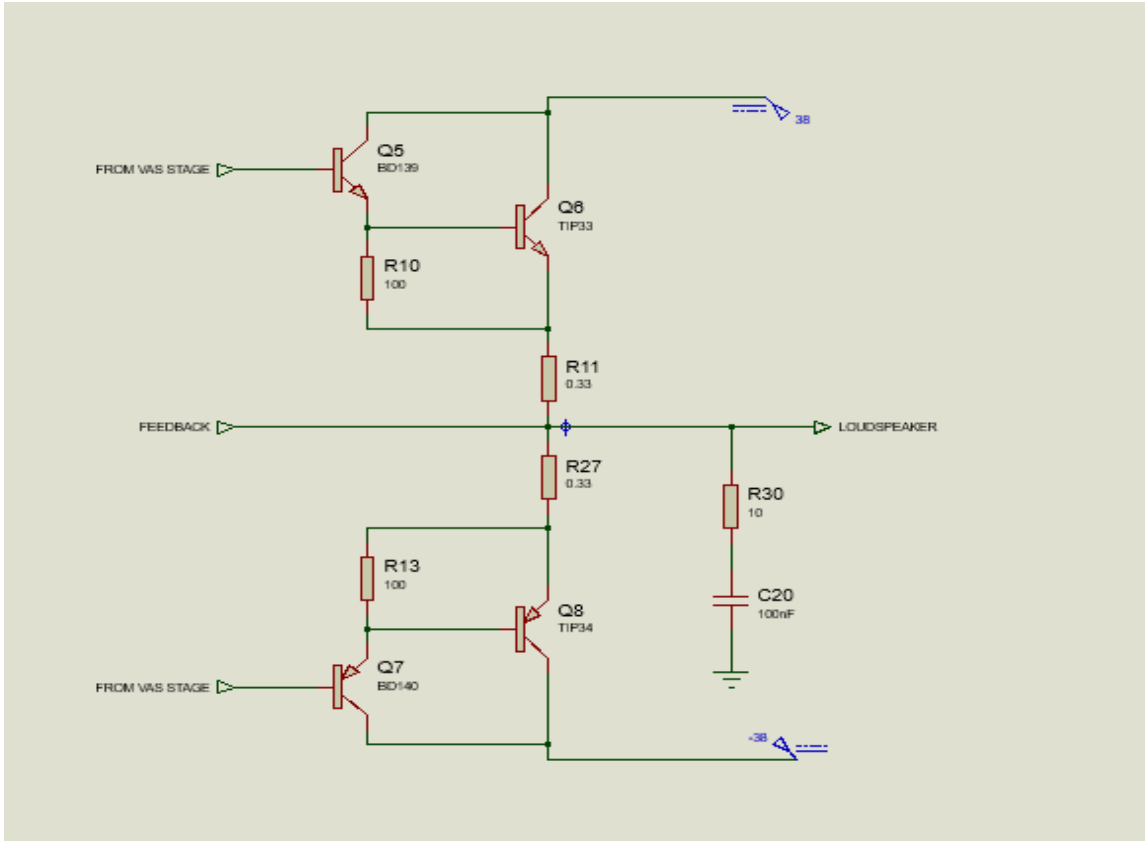


Figure 9 Darlington Complementary Output Stage

The above figure of a basic output stage is a double emitter follower, a NPN pair of Q5 and Q6 for the positive output currents and a PNP pair of Q7 and Q8 for negative output currents. Q6 (TIP33) and Q8 (TIP34) are complementary high power transistor that pass large currents therefore heat sinks were attached to both transistors for heat dissipation. The other transistors, Q5 (BD139) and Q7 (BD140) are driver transistors in the common arrangement operate in class AB so they turn OFF shortly after the output transistor turns OFF.

DARLINGTON OUTPUT STAGE CALCULATION

From the figure of the output stage above, using an 8 ohm load and a VCC of 38V and VEE of -38V, ignoring a very small voltage drop at R11, the output current, I_{out} is;

$$I_{out} = \frac{V_{CC}}{R_L} = \frac{38}{8} = 4.75 A$$

The total gain of the NPN Darlington connection consisting of Q5 and Q6 is;

$$\beta_1 \text{ for Q5 is } 40$$

$$\beta_2 \text{ for Q6 is } 20$$

$$\begin{aligned}\beta &= \beta_1 * \beta_2 \\ &= 40 * 20 = 800\end{aligned}$$

Calculation of I_{B5} for Q5

$$I_{B5} = \frac{I_{out}}{\beta} = \frac{4.75A}{800} = 5.94 \text{ mA}$$

Current at Bias Spreader

$$I_{\text{current source}} (I_{c4}) = 4 \text{ times } I_B$$

$$I_{c4} = 5.94\text{mA} * 4 = 23.75\text{mA}$$

Q9 is the driver transistor and its base current I_{B9} can be found as follows;

$$I_{B9} = \frac{I_{B5} + I_{E4}}{\beta_9} = \frac{23.75\text{mA} + 5.94\text{mA}}{40} = 0.73\text{mA}$$

I_{c1} is supposed to be able to practically supply enough current to make transistor Q9 to conduct. Due to that it is assumed that I_{c1} has to be five times I_{B9} , i.e.

$$I_{B9} = 0.74\text{mA}$$

$$I_{c1} = I_{B9} * 5$$

$$I_{c1} = 3.7\text{mA}$$

Finding R_1

$$R_1 = \frac{0.7V}{3.7\text{mA}} = 189\Omega$$

Finding I_{tail}

$$I_{tail} = 2 * I_{c1}$$

$$= 2 * 3.7\text{mA} = 7.4\text{mA}$$

Finding R_{tail}

$$R_{tail} = \frac{37.5V}{7.4\text{mA}} = 5.067\text{k}\Omega = 5.1\text{k}\Omega$$

Voltage Amplification stage

This stage provides all the voltage gain as its name suggests. It consists of a;

- Driver transistor,
- A bias spreader and
- A current source for bootstrapping.

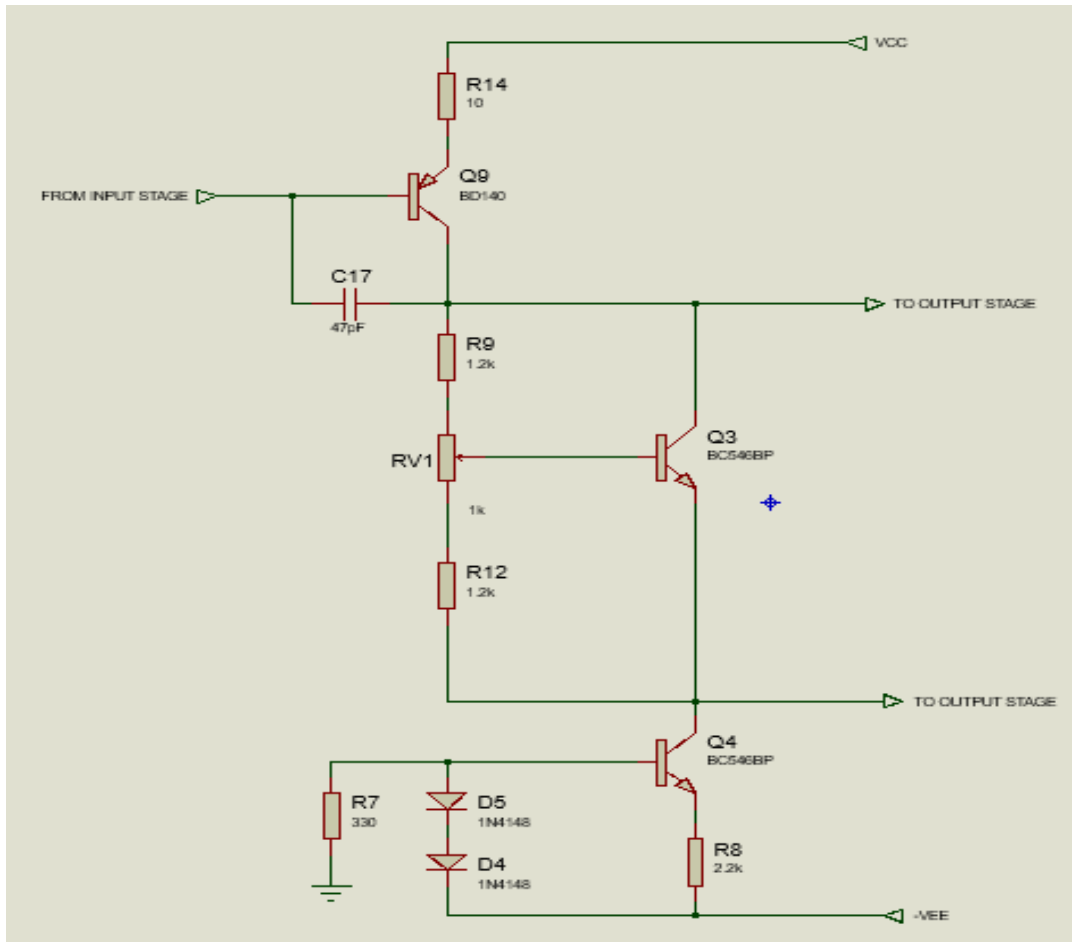


Figure 10 VAS stage

Driver Transistor

Most of the open loop voltage gain of the amplifier is provided by the transistor Q9 while the 47pF capacitor determines the dominant pole. The dominant pole is the pole which dominates the step response of a system. This capacitor represents the miller-capacitor dominant-pole compensation where the collector pole of transistor Q9 is lowered by adding external miller-capacitance, 47pF, to that which exists as internal capacitance of Q9. The 47pF capacitor causes pole-splitting while also playing a critical role in stabilizing the negative feedback loop around the amplifier.

Bias Spreader

This stage is also known as a preset. It is used when a voltage drop equal to a multiple of V_{be} drop is needed. The required bias voltage for the output stage is developed across the bias spreader which is usually a V_{be} multiplier design around Q3.

The components R9, R12, VR1 and the transistor Q3 make up the bias spreader which controls the quiescent current by setting it to minimum through adjusting the variable resistor VR1 we can adjust level of idle current or the amount of bias voltage. This process of controlling the quiescent current protects the output transistors by balancing the current supplied to the upper and lower output transistors.

CURRENT SOURCE

The transistor Q4 is a constant current source that ensures that the PNP Darlington complementary output transistor receives adequate voltage drive under large signal conditions. One diode drop is impressed across the 2.2k Ω resistor to generate the desired current. Together the diodes 1N4148 only drop about 1.1 volts.

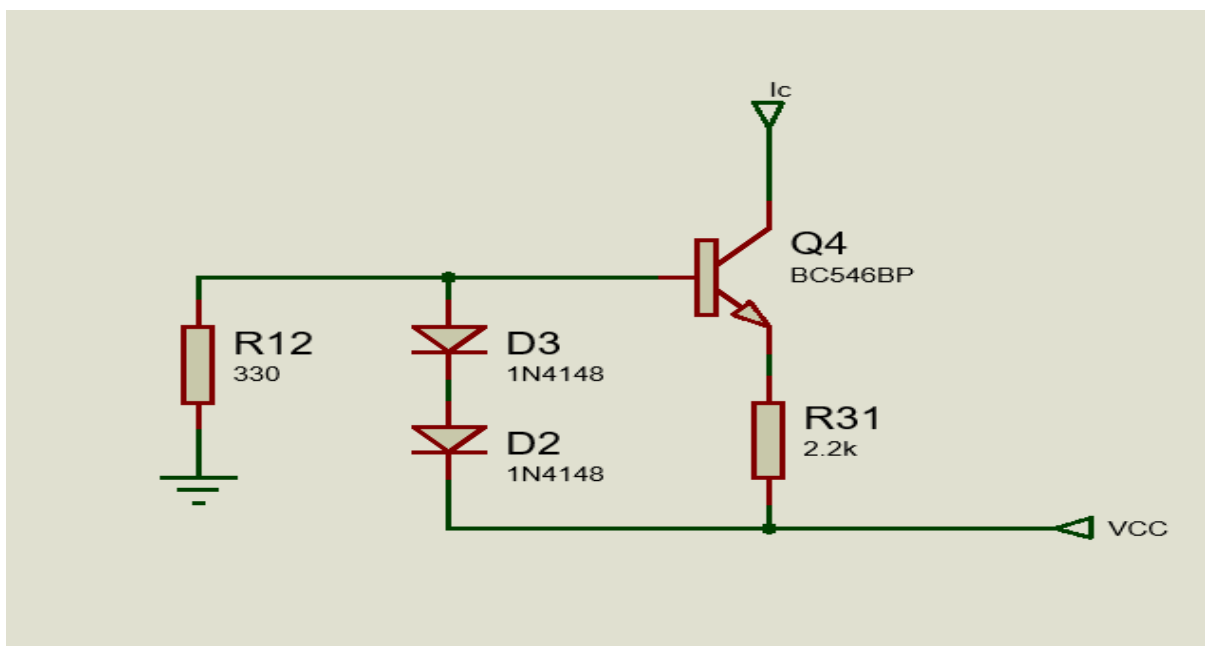


Figure 11 Current Source

CALCULATIONS

DC ANALYSIS

$$\begin{aligned} V_B &= (V_{D3} + V_{D2}) + (-V_{EE}) \\ &= 0.7V + 0.7V + -38 \end{aligned}$$

$$= 1.4V - 38V$$

$$= -36.6V$$

$$V_E = V_B - V_{BE}$$

$$= -36.6V - 0.7V$$

$$= -37.3V$$

$$V_{RE} = V_E - (-V_{EE})$$

$$= -37.3V + 38V$$

$$= 0.7V$$

$$I_C = \frac{V_{RE}}{R_E} = \frac{0.7V}{2.2k\Omega} = 0.32mA$$

	Calculation	Simulation	% Error	Calculation	Hardware	% Error
V_B	-36.6V	-36.27V	0.90%	-36.6V	-36.73V	0.36%
V_E	-37.3V	-36.89V	1.1%	-37.3V	-37.54V	0.64%
V_{RE}	0.7V	0.7V	0%	0.7V	0.66V	5.7%
I_C	0.32mA	0.43mA	3.4%	0.42mA	0.5mA	5.6%

Table 1 current source results

INPUT STAGE

The input stage of the amplifier is a double-ended input, single-ended output differential amplifier referred to as the long-tailed pair (LTP). It is called a long-tailed pair because it is supplied with tail current from very high impedance circuit mostly a current source. The input signal to the amplifier from the source is in mill volts range and it is very weak to drive the succeeding stages.

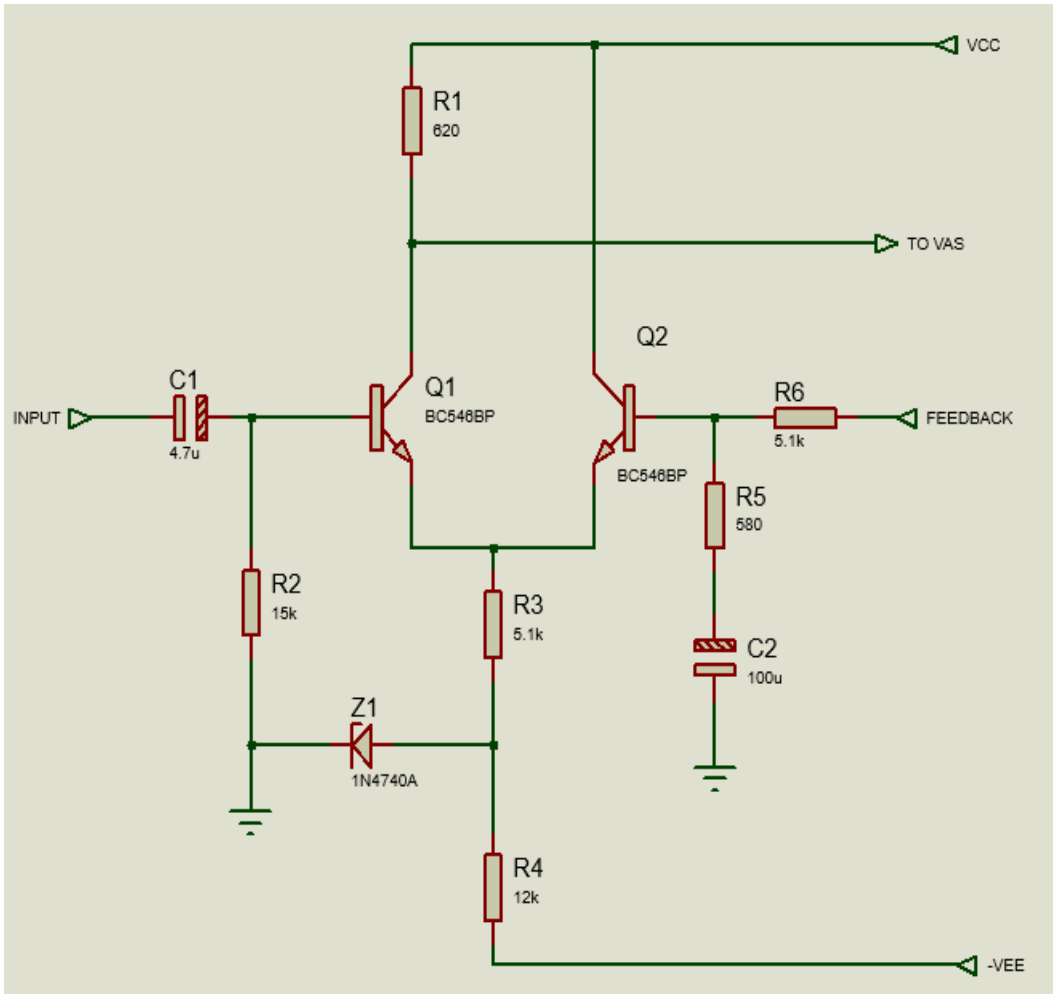


Figure 12 Input Stage

The transistors Q1 and Q2 form the differential pair. This stage is usually characterized by a fairly low voltage gain ranging from 1 to 15. The resistors R5 and R6 are feedback resistors used to implement a voltage divider which determines the feedback fraction of the output signal to the input signal. These resistors set the AC voltage gain.

$$AC \text{ voltage gain} = \frac{R6}{R5} = \frac{5.1k\Omega}{580\Omega} = 8.79$$

In dB, gain = $20\log_{10} 8.79 = 18.88 \text{ dB}$

R3 (also known as R_{tail}) and the zener diode Z1, determine the total current in the differential pair of Q1 and Q2. The resistor R5 in series with the capacitor C2 create a complete negative feedback at DC. This in collaboration with the differential pair ensures that the output voltage of the amplifier is zero when no signal is at the input.

The current fed to the Voltage Amplification Stage is approximately 5 times less than the current I_{c1} , that is, I_{c1} is supposed to be able to practically supply enough current to make transistor Q9 in the VAS stage to conduct. Due to that it is assumed that I_{c1} has to be five times I_{B9} , i.e.

$$I_{B9} = 0.73mA$$

$$I_{c1} = I_{B9} * 5$$

$$I_{c1} = 3.7mA$$

Finding R_1

$$R_1 = \frac{0.7V}{3.7mA} = 189\Omega$$

Finding I_{tail}

$$I_{tail} = 2 * I_{c1}$$

$$= 2 * 3.7mA = 7.4mA$$

Finding R_{tail} (R_3)

$$R_{tail} = \frac{37.5V}{7.4mA} = 5.067k\Omega = 5.1k\Omega$$

The input impedance was calculated and found to be $Z_{IN} = 150 k\Omega$

Short Circuit Protector

Short circuit protection involves monitoring the current in the output devices and restricting the drive applied to the output stage whenever excessive current is detected. The following circuit was designed as a short circuit protector;

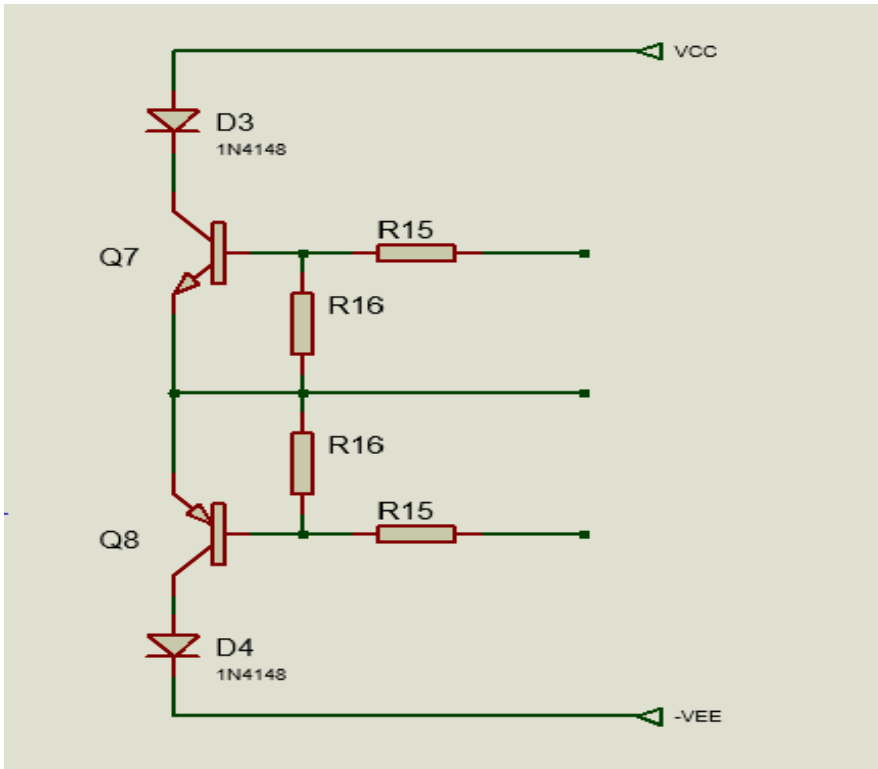


Figure 13 Short Circuit Protector

Resistors R15 and R16 form a voltage divider sensing the emitter current of the output devices. When there is excessive emitter current, Q7 takes base drive from the NPN Darlington complementary output transistors while Q8 takes base drive from the PNP complementary Darlington transistors. The diodes D3 and D4 prevent Q7 and Q8 from having their collector to base junctions forward biased under normal operating conditions.

ACTIVE FILTER

Sallen-Key Topology

This is an electronic filter topology used to implement second-order active filters. This topology is mostly preferred due to its simplicity, high input impedance and an easily selectable gain. It is a degenerate form of a voltage-controlled voltage-source (VCVS). This filter uses a super-unity gain voltage amplifier with practically infinite input impedance and zero output impedance to implement a two pole low-pass, high-pass and band-pass response.

This topology uses a unity gain operational amplifier with an assumption that it is ideal. It often uses the operational amplifier configured as voltage follower.

DESIGN

During design, we choose the quality factor, Q and threshold frequency, F_o appropriate for their application. The quality factor is critical in determining the eventual shape of the frequency response curve. These two values assist in the determination of the other filter component values as follows; the ratio between $C1$ and $C2$ is set as n and the ratio between $R1$ and $R2$ as m . So,

$$R1 = mR,$$

$$R2 = R,$$

$$C1 = nC,$$

$C2 = C$. therefore, F_o and Q are

$$\omega_o = 2\pi F_o = \frac{1}{RC\sqrt{mn}}$$

And
$$Q = \frac{\sqrt{mn}}{m+1}.$$

Low Pass Filter

An operational amplifier is used as a buffer.

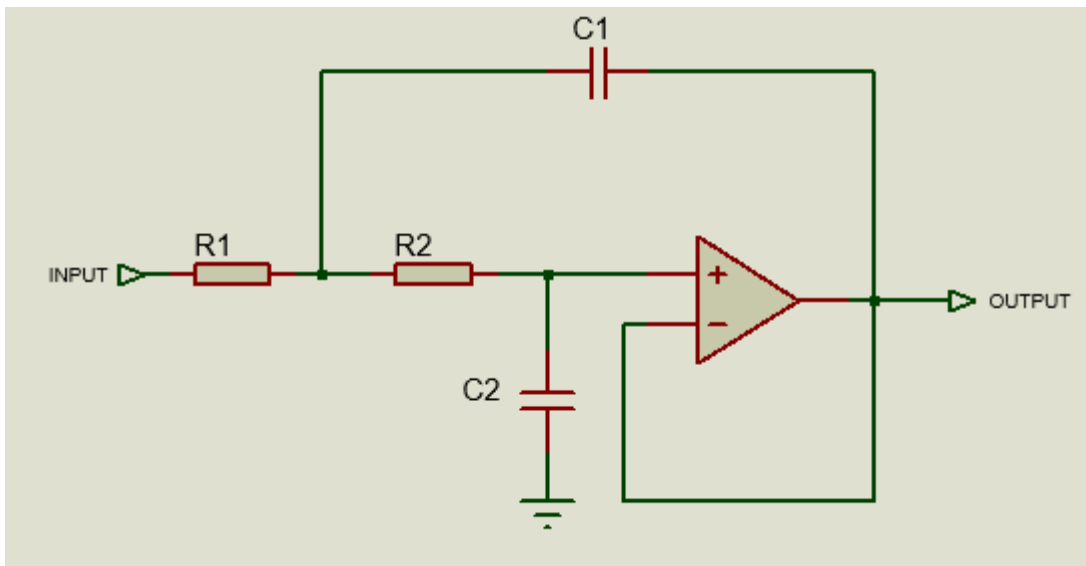


Figure 14 Low Pass Filter

Taking F_o to be 1.2kHz and Q to be 0.5, we set R_1 to be 12k Ω , and calculate the other unknown parameters as follows;

$$Q = \frac{\sqrt{mn}}{m+1} = \frac{1}{2} = 0.5 \quad \text{Where } m=1 \text{ and } n=1$$

$$\omega_{o1} = 2\pi F_o = \frac{1}{RC\sqrt{mn}} = 2 * 3.142 * 1200 = 7539.822$$

$$\omega_{o2} = \frac{1}{RC\sqrt{mn}} = \frac{1}{12000C\sqrt{1}} = \frac{1}{12000C}$$

$$\omega_{o1} = \omega_{o2}$$

$$7539.822 = \frac{1}{12000C}$$

Therefore, $C = 0.01\mu\text{F}$ through the ratios m and n , we get $C_1 = 0.01\mu\text{F}$, $C_2 = 0.01\mu\text{F}$ and $R_1 = 12\text{k}\Omega$, $R_2 = 12\text{k}\Omega$

High Pass Filter

This is a second order unity gain high-pass filter.

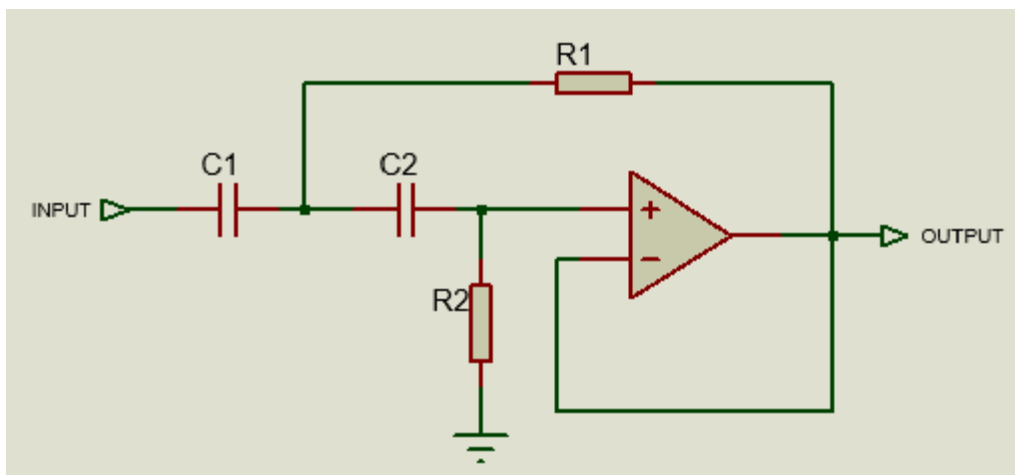


Figure 15 High Pass Filter

To determine the values of the components, we pick resistor values then calculate the capacitor values as follows;

Let $R_1 = R_2$ be 27000 $\Omega = 27\text{k}\Omega$,

For a threshold frequency, f_o of 6 kHz,

$$f_o = \frac{1}{2\pi\sqrt{R1 * R2 * C1 * C2}}$$

For $R1=R2=R$ and $C1=C2=C$, $f_o = \frac{1}{2\pi\sqrt{R^2 * C^2}}$

$$6000 = \frac{1}{2\pi\sqrt{27000^2 * C^2}}$$

$$C1 = C2 = C = 0.98 * 10^{-9}F = 1nF \text{ OR } 0.001\mu F$$

Band-pass Filter

A band-pass filter works to screen out frequencies that are too low or too high, giving ease passage only to frequencies within a certain range.

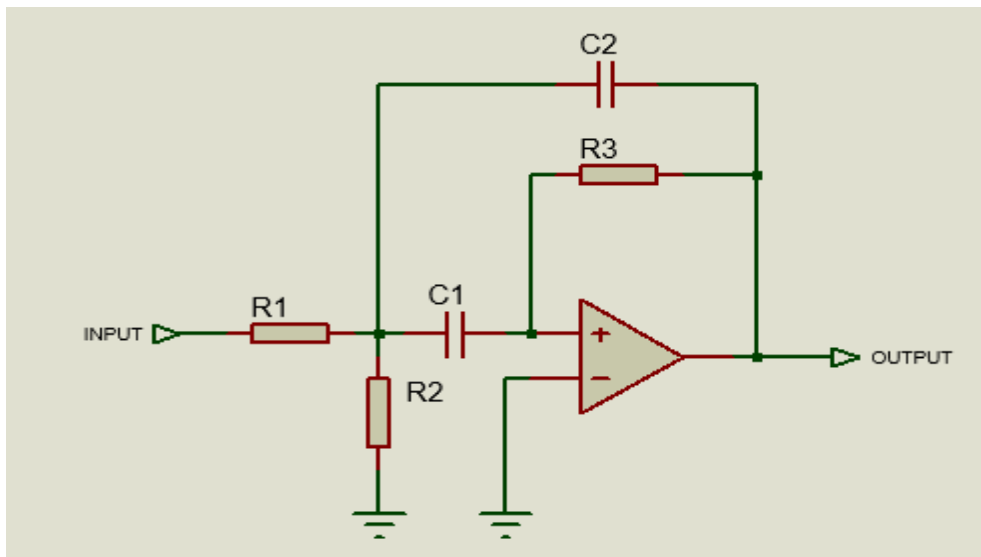


Figure 16 Band Pass Filter

$$f_c = \frac{1}{2\pi} \sqrt{\frac{1}{R3 * C1 * C2} \left(\frac{1}{R2} + \frac{1}{R2} \right)}$$

Where f_o is the centre frequency = 3.5 kHz

$$\frac{v_o}{v_i} = \frac{2\zeta(2\pi f_o)Ks}{s^2 + 2\zeta(2\pi f_o)s + (2\pi f_o)^2}$$

Where v_o =output voltage

V_i = input voltage

ζ = damping ratio = 1

$$Q = \frac{1}{2\zeta} = 0.5$$

$$K = \frac{R3}{R1} * \frac{-C2}{C1 + C2} = -1$$

Where K is the gain at center frequency, and Q is the quality factor.

Using the above equations, we determine that;

$$R1=4.7K\Omega$$

$$C1=0.0047\mu F=4.7nF$$

$$R2=4.7k\Omega$$

$$C2=0.033\mu F= 33nF$$

$$R3=5.6K\Omega$$

Power Supply

This is a device that supplies electrical power to another unit. This device obtains its prime power from the ac power line or from special power systems such as motor generators, inverters and converters. A simple dc power supply consists of different components namely;

- i. An isolating transformer to step-down the voltage and also to solve the humming problems between the line and power supply,
- ii. A full-wave bridge rectifier in series to the load which is used to perform rectification by allowing current to pass in only one direction,
- iii. Capacitor filter that employs a capacitor at its input to stabilize the voltage by storing up energy to the load between pulses and other smaller capacitors to reduce ac and also reduce the ripple component of the dc power supply
- iv. Voltage regulators may also be used to drop the voltage to the required range.

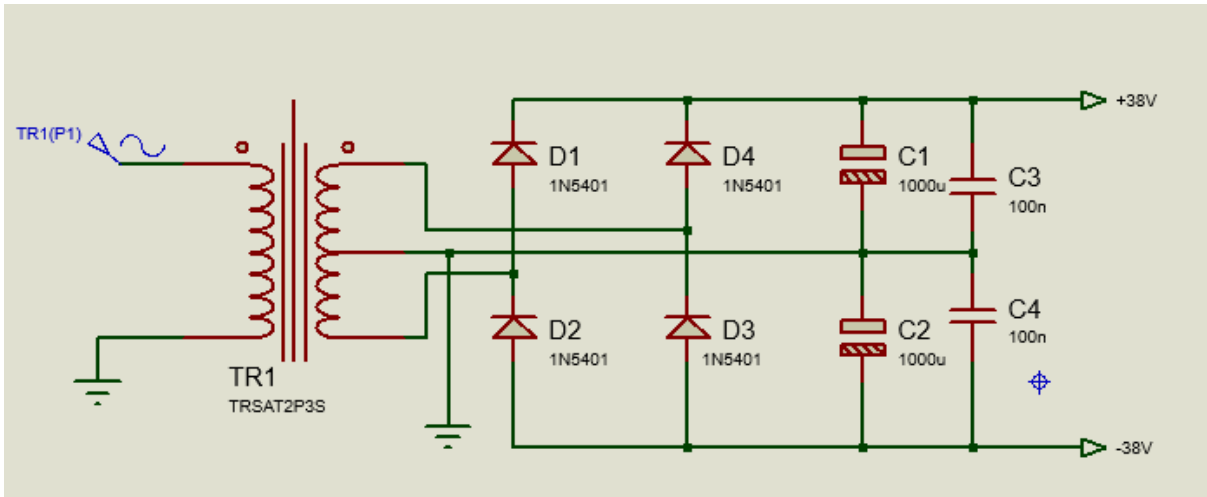


Figure 17 Power Supply

Determining the current per rectifier

$$\begin{aligned}
 I_{rect} &= 0.5 * I_{dc} \\
 &= 0.5 * 4.75 = 2.375 A
 \end{aligned}$$

Where 0.5 is a constant and I_{dc} is the rectified ac current (dc current)

AC voltage required from the transformer

$$\begin{aligned}
 V_{ac} &= 1.11 * V_{dc} \\
 &= 1.11 * 24.32 \\
 &= 27 V_{rms}
 \end{aligned}$$

Where 1.11 is a constant and V_{ac} is the transformer voltage,

Peak Inverse Voltage (PIV)

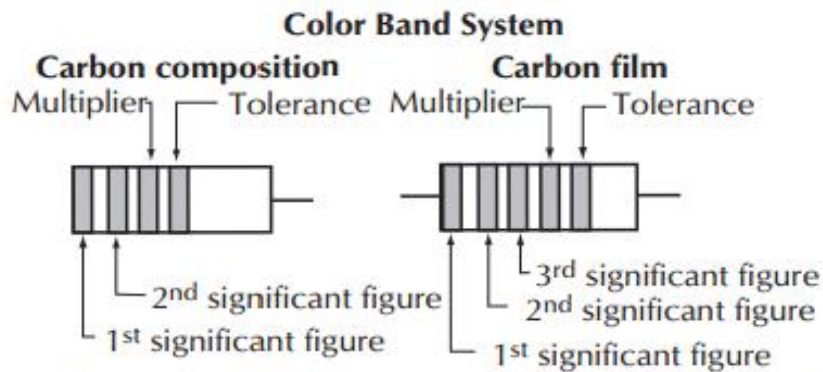
$$\begin{aligned}
 PIV &= 2.82 * V_{ac} \\
 &= 2.82 * 27 \\
 &= 76.14 V_{rms}
 \end{aligned}$$

Where, V_{ac} is the secondary ac voltage per leg.

CIRCUIT COMPONENTS

Resistors

A resistor is a device connected into an electrical circuit to introduce a specified resistance. Resistance is measured in ohms and as stated in ohm's law, the current through a resistor is directly proportional to the voltage across it and inversely proportional to the resistance.



Resistors with black body are composition, noninsulated.
 Resistors with colored body are composition, insulated.
 Wirewound resistors have the 1st color band double width.

Color	Digit	Multiplier	Tolerance	Failure Rate
Black	0	1	—	—
Brown	1	10	±1%	1.0
Red	2	100	±2%	0.1
Orange	3	1000	±3%	0.01
Yellow	4	10,000	±4%	0.001
Green	5	100,000	—	—
Blue	6	1,000,000	—	—
Violet	7	10,000,000	—	—
Gray	8	100,000,000	—	—
White	9	—	—	Solderable*
Gold		0.1	±5%	—
Silver		0.01	±10%	—
No Color			±20%	—

Table 2 Resistor color bands

Resistors are rated to dissipate a given wattage without exceeding a specified standard temperature. The differences in standard conditions affect the temperature rise and therefore affect the wattage at which the resistor may be used in a specific application.

To select a resistor for a specific application, the following steps were followed;

- i. Determine the resistance
- ii. Determine the watts to be dissipated by the resistors,
- iii. Determine the proper watt size as controlled by watts, volts, permissible temperatures, mounting conditions and circuit conditions.

- iv. Choose the most suitable kind of unit, including type, terminals and mounting

Diodes

The diode is a device that is characterized by a low resistance to current flow in one direction and a high resistance in the other. A forward biased diode presents a very low resistance to current flow while in a reverse-biased diode; no current should flow regardless of the value of the voltage put across the diode.

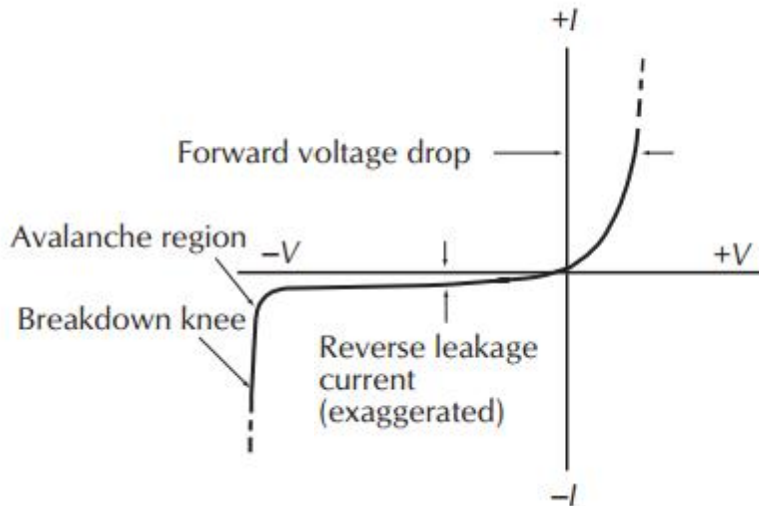


Figure 18 Characteristic curve

Zener Diode

In zener diodes, the breakdown characteristic is deliberately made as vertical as possible in the zener region so that the voltage across the diode is essentially constant over a wide reverse-current range acting as a voltage regulator.

This type of diode functions as a voltage reference.

Capacitors

Capacitors are used in circuits for both AC and DC applications. In AC circuits capacitors are used to block DC, allowing only AC to pass, bypassing AC frequency, or discriminating between higher and lower AC frequencies while in DC circuits capacitors are used to store and release energy such as filtering power supplies and for providing on demand a single high voltage pulse of current. The value of the capacitor is normally written on the capacitor or a code representing the value is written instead. In a circuit with a pure capacitor, the current leads the voltage by 90° . When a capacitor is used in an AC circuit, the capacitive reactance or the impedance the capacitor injects into the circuit is calculated as follows;

$$X_c = \frac{1}{2\pi FC}$$

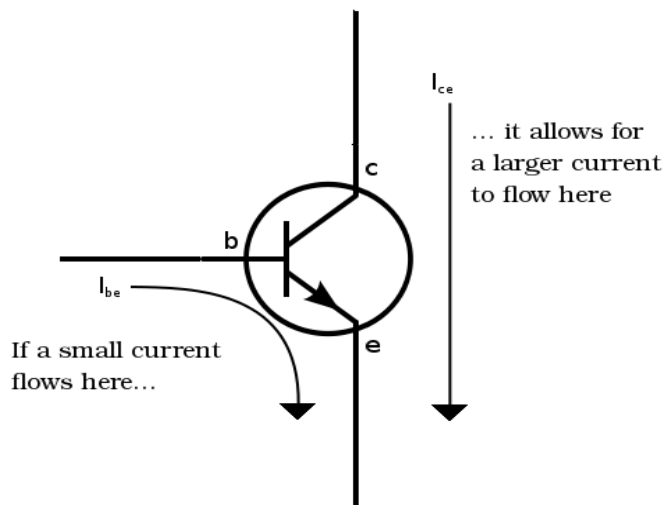
Where X_c is the capacitive reactance, and F is the frequency in hertz and C is the capacitance in farads

Uses of Capacitors

- | | | |
|----------------|-------------------|--------------------|
| i. Filter | vi. Start motors | xi. Suppress noise |
| ii. Tune | vii. Feed through | xii. Bypass |
| iii. Couple | viii. Compensate | xiii. Pass AC |
| iv. Block DC | ix. Isolate | |
| v. Shift phase | x. Store energy | |

Transistors

A transistor is a semiconductor device used to amplify or switch electronic signals and electrical power. Transistors are named by the way they are made. During the making of the material for a junction, the impurity content of the semiconductor is altered to provide NPN or PNP regions. There are two types of transistors, a bipolar junction transistor (BJT) with terminals labeled base, collector and emitter and field effect transistor (FET) with terminals labeled gate, source and drain.



A bipolar junction transistor is the primary building block of most audio power amplifiers.

Heat sinks

Electrical systems are powered by smaller devices packaged in smaller systems that generate heat. To manage the heat generated and dissipated, heat sinks are attached to these devices or components to conduct the heat and prevent the devices from damage. Heat sinks manage the heat generated through heat transfer and there are three forms of heat transfer, namely;

- i. Convection

This is transfer of heat from a solid surface to the surrounding air. This method drives the amount of required fin surface area that is accessible to the surrounding air and allows it to move away and the process is repeated over and over leaving cooling effect. This process can be made quicker by use of a fan to blow away the heated air.

ii. Conduction

This is the transfer of heat from solid to the next adjacent solid. The amount of heat transfer depends on the surface finishes and the interfacial pressure generated by the attachment system. This mechanically generated force is accomplished by screws, springs, and snap assemblies.

iii. Radiation

This method of heat transfer is the least important for heat sinks. It has a maximum 20-25% impact in natural convection applications with negligible impact.

Characteristics of a good heat sink

- i. High heat sink surface
- ii. Good aerodynamics
- iii. Good thermal transfer within the heat sink
- iv. Very flat contact area

POWER AMPLIFIER PERFORMANCE SPECIFICATION

Distortion

This is the alteration in shape of an audio waveform. The most common distortion is total harmonic distortion (THD). This distortion is usually specified at one or two frequencies or over a range of frequencies. In practice, the total harmonic distortion specification is described as THD+N; where TDH is the total harmonic distortion and N represents the noise. Noise is any unwanted sound or signal emanating from a speaker system. This is how total harmonic distortion is often measured. At high power testing levels, the true THD will often dominate the noise, but at lower power levels the measurements mostly reflect the noise rather than the actual total harmonic distortion being measured.

Clipping

Clipping is a form of distortion that limits a signal once it exceeds a threshold. In a power amplifier, clipping occurs when the power amplifier is forced past its maximum output power, that is, the output voltage of the amplifier is equal to the supply from its power supply and can't go any higher. The peaks of the signal, both positive and negative, are clipped off. Clipping causes the compression of the signal and this causes the average power to increase and it may be over the amplifier's maximum thermal capabilities hence the amplifier may overheat.

A clipped signal loses low frequency content due to the fact that low frequencies have larger amplitude than high frequencies. Clipping can cause damage to tweeters and also woofers

Frequency response

A full audio band ranges from frequency around 20 Hz up to over 20 kHz. In designing a power amplifier, the frequency response must extend over the full audio band within a reasonable tolerance. The frequency response of power amplifiers is as follows;

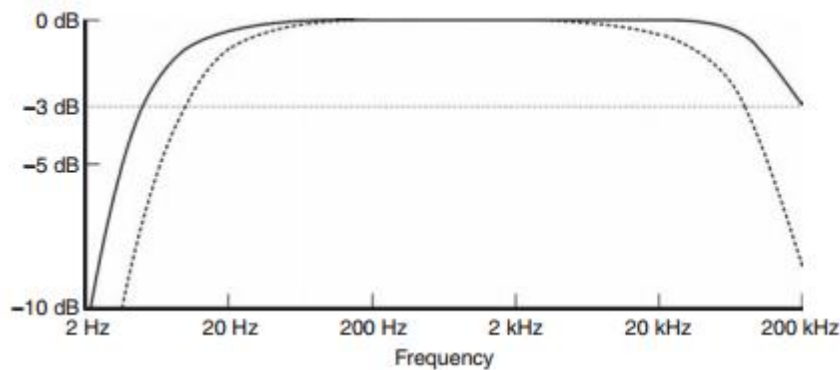


Figure 19 Power Amplifier Frequency response

While the tolerance assigned to the frequency response of loudspeakers is often $\pm 3\text{dB}$. The bandwidth of the system is specified by the point where the amplifier is down by 3dB from the normal 0dB reference. This bandwidth is called the 3dB bandwidth.

Output Current

The output current can also have a strong influence on sonic quality. The complex reactive loudspeaker load attached to amplifiers can demand larger currents than the rated resistive load with which an amplifier is often tested.

Rated Output Power

Maximum output power is almost always quoted for a load of $8\ \Omega$ and is often quoted for a load of $4\ \Omega$ as well. A given voltage applied to a $4\text{-}\Omega$ load will cause twice the amount of current to flow, and hence twice the amount of power to be delivered. Ideally, the output voltage of the power amplifier is independent of the load, both for small signals and large signals. This implies that the maximum power into a $4\text{-}\Omega$ load would be twice that into an $8\text{-}\Omega$ load. In practice, this is seldom the case, due to power supply sag and limitations on maximum available output current. The correct terminology for power rating is continuous average sine wave power, as in 100-W continuous average sine wave power. However, many often take the liberty of using the term W RMS.

Slew rate

Slew rate is the maximum rate of voltage change that an amplifier can achieve or the measure of how fast the output voltage of the power amplifier can change under large-signal conditions. Slew rate is specified in volts per microsecond. It is used as an indicator of how well a power amplifier can respond to high level transient content.

Slew rate in an audio amplifier is directly proportional to the maximum current that the input stage is capable of handling which is limited to the switching of the tail current to one side of the circuit configuration. (Cordell, 2011)

CHAPTER 4: RESULTS AND SIMULATIONS

Circuit Diagram

The 100W Power Amplifier design with Darlington Complementary output transistors was as follows;

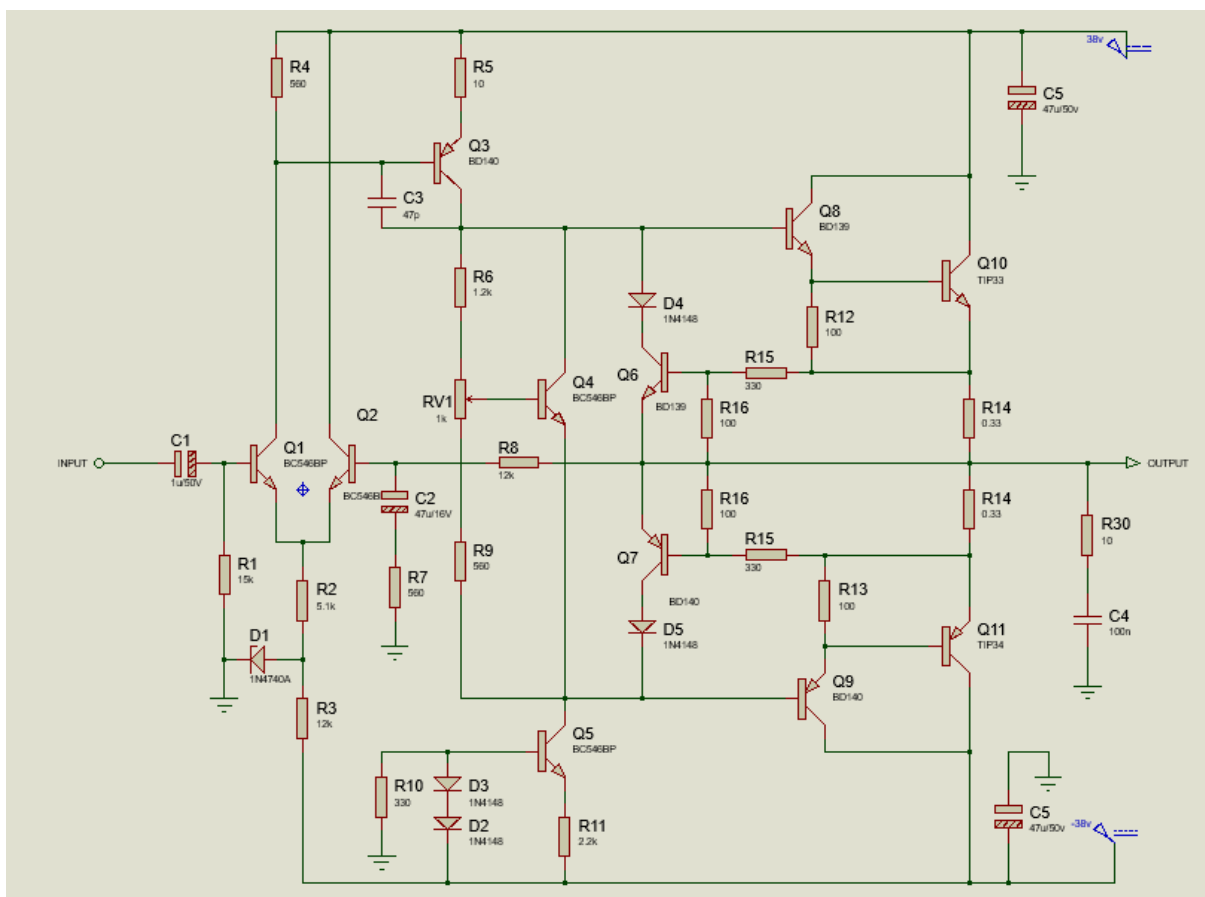


Figure 20 100w Power Amplifier

Circuit Calculations

Maximum power in the Output Transistors

- i. Output Power for the AC signal at 1.2 kHz

$$\begin{aligned} P_{l(ac)} &= I_{lrms} * V_{lrms} \\ &= \frac{V^2_{l(peak)}}{2Rl} \\ &= \frac{V^2_{l(p-p)}}{8Rl} \\ &= \frac{76.14^2}{8 * 8} = \frac{5797.3}{64} = 90.58 W \end{aligned}$$

- ii. DC input power to the amplifier;

$$\begin{aligned} P_{in} &= I_c(dc) * V_{cc} \\ &= I_c(ac) * V_{cc} \\ &= \frac{2}{\pi} I_{l(ac)} * V_{cc} \\ &= \frac{2}{\pi} * \frac{V_{l(p)}}{Rl} * V_{cc} \\ &= \frac{2}{\pi} * \frac{38}{8} * 38 \\ &= 114.9 W \end{aligned}$$

Efficiency of the Power Amplifier

$$\text{efficiency, } \eta = \frac{\text{average ac power delivered to the load}}{\text{total dc power supplied to the load}} * 100$$

$$\begin{aligned} \eta &= \frac{P_{l(ac)}}{P_{in(dc)}} * 100 \\ &= \frac{\pi}{4} * \frac{V_{l(peak)}}{V_{cc}} * 100 \\ &= \frac{\pi}{4} * \frac{39.15}{38} * 100 = 74.4\% \end{aligned}$$

Power Dissipation

When a signal is present, the power dissipation of a transistor decreases because the transistor converts some of the quiescent power to signal power. For this reason, the quiescent power dissipation is the worst case. Therefore, the power rating of a transistor in an amplifier must be greater than $P(D/2Q)$; otherwise, the transistor will be destroyed.

$$\begin{aligned}P\left(\frac{d}{2Q}\right) &= P I(dc) - P I(ac) \\&= \frac{2}{\pi} * \frac{V I(peak)}{Rl} * V_{cc} - \frac{V I(peak)}{2Rl} * V_{cc} \\&= \frac{V_{cc}^2}{Rl} \left(\frac{2}{\pi} - \frac{1}{2}\right) \\&= \frac{38^2}{8} \left(\frac{2}{\pi} - \frac{1}{2}\right) = 24.66W\end{aligned}$$

For one output transistor, the power dissipated is;

$$P\left(\frac{d}{Q}\right) = \frac{P\left(\frac{d}{2Q}\right)}{2} = \frac{24.66W}{2} = 12.33 W$$

Computer Simulation Results

Computer simulation was done using PROTEUS 8.1 software. The analysis was done for frequency range of 20Hz to 100 KHz. The following were the results from the simulated design for an input of 1Vp;

POWER AMPLIFIER SIMULATION RESULTS

Input Signal(Vp), V	Frequency(F), Hz	Output Voltage(Vrms)
0.3	20	2.55
0.3	50	2.95
0.3	100	3.00
0.3	300	3.05
0.3	500	3.05
0.3	800	3.05
0.3	1k	3.05

0.3	2k	3.05
0.3	4k	3.05
0.3	10k	3.05
0.3	15k	3.05
0.3	20k	3.05
0.3	50k	3.05
0.3	80k	3.05
0.3	100k	3.05

Table 3 Power Amplifier simulation results

Results

Simulation

Input Signal(Vp), V	Output Voltage(Vrms), V	Output Current(Irms), A	Output Power(Wrms)
2	20.25	4.75	96.186

Table 4 Output Power simulation

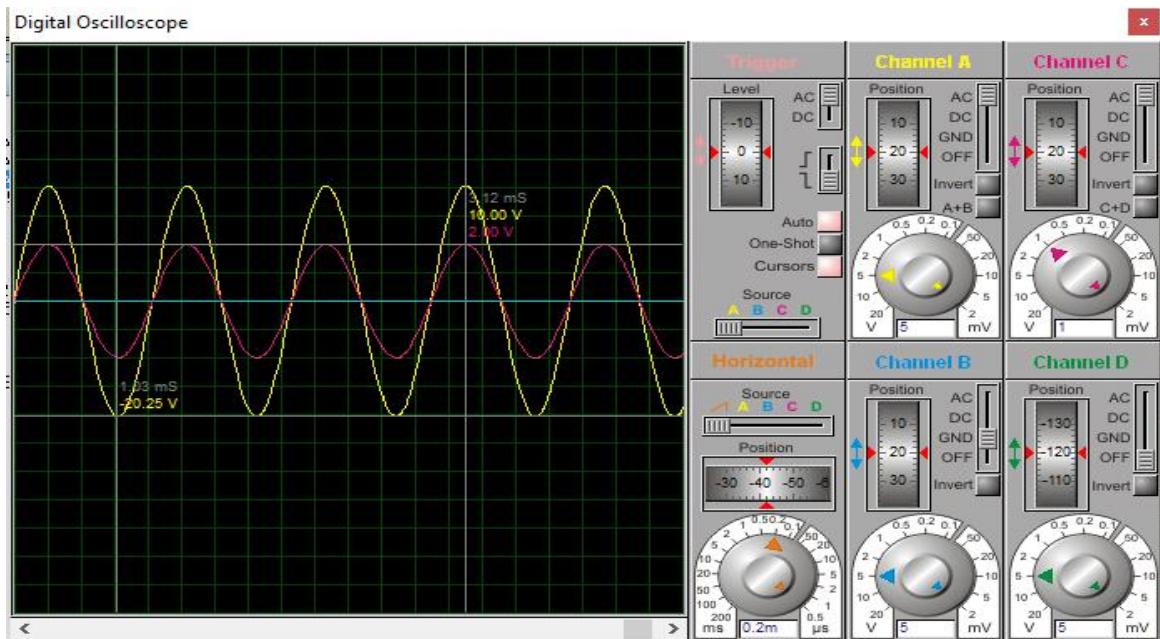


Figure 21 Amplifier Simulated Waveform

Laboratory Implementation

Input Signal(Vp), V	Output Voltage(Vrms), V	Output Current(Irms), A	Output Power(Wrms)
2	19.7	4.125	81.2625

Table 5 Laboratory results

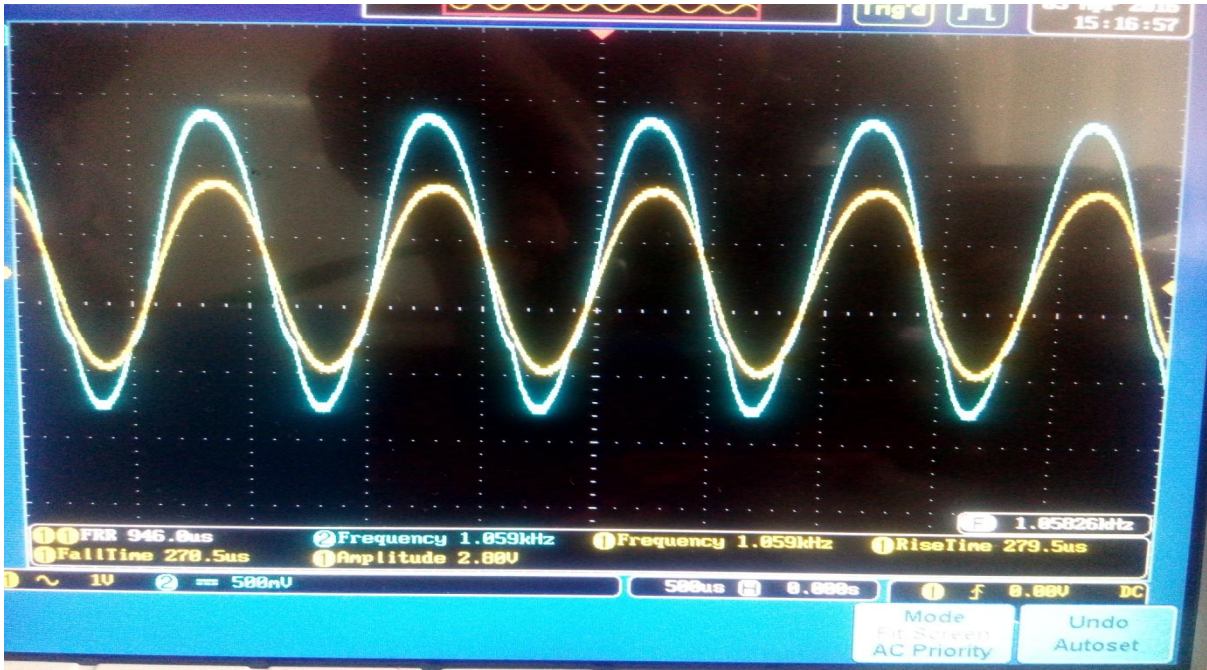


Figure 22 Laboratory Waveform

POWER AMPLIFIER FREQUENCY RESPONSE

FREQUENCY (KHz)	$V_{IN}(V)$	$V_{OUT}(V)$	GAIN
1	1	18.3	18.3
10	1	18.4	18.4
20	1	18.4	18.4
30	1	18.5	18.5
40	1	18.5	18.5
50	1	18.5	18.5
60	1	18.7	18.7
70	1	18.7	18.7
80	1	18.7	18.7
90	1	18.8	18.8
100	1	18.8	18.8

Table 6POWER AMPLIFIER FREQUENCY RESPONSE

FILTER DESIGN SIMULATION RESULTS

A signal generator was connected to the input of the circuit and a CRO at the output as shown below. The signal generator was adjusted such that it gave out a voltage of 5 divisions peak at 0.2v/div. This translated to an input voltage of 1Volt peak.

LOW-PASS FILTER

The following results were obtained for the unity gain low pass filter with a cut-off frequency of 1.2 kHz.

Signal Amplitude, V(peak)	Signal Frequency, Hz	Output Amplitude, V(peak)
1	20	1
1	50	1
1	100	1
1	300	0.95
1	500	0.85
1	800	0.725
1	1k	0.65
1	1.2k	0.55
1	1.5k	0.425

Table 7 Low Pass Filter

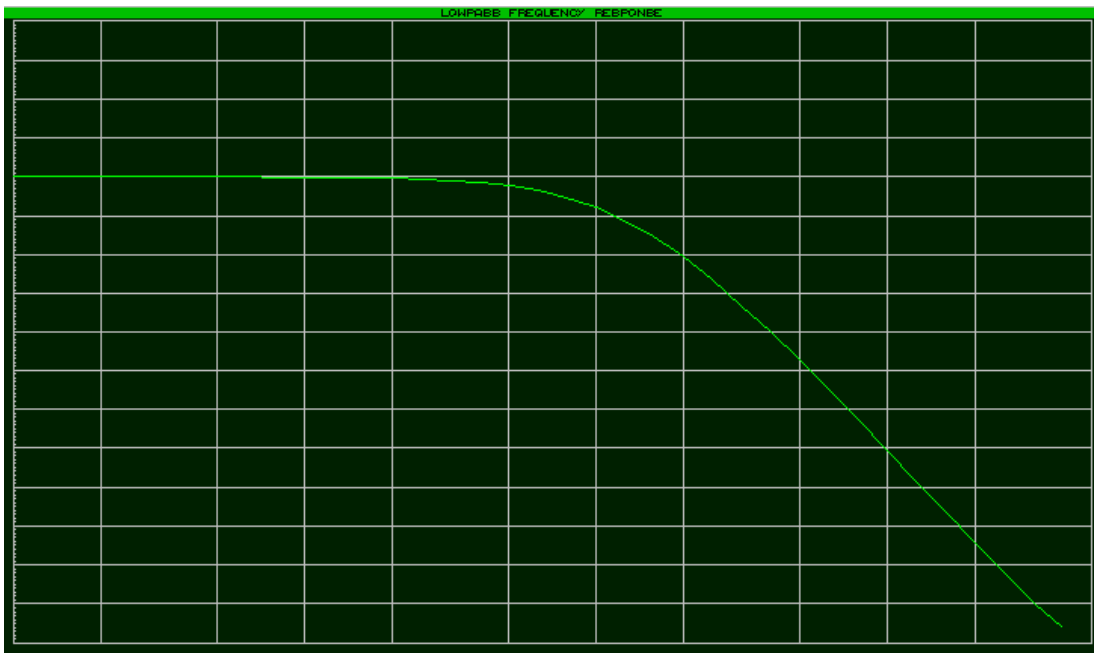


Table 8 Low Pass Filter

BAND-PASS FILTER

The following results were obtained for the band pass filter with a lower cut-off frequency of 1.2 kHz and a higher cut-off frequency of 6 kHz.

Signal Amplitude, V(peak)	Signal Frequency, Hz	Output Amplitude, V(peak)
1	1.2k	0.55
1	1.5k	0.65
1	1.8k	0.725
1	2k	0.85
1	3k	0.975
1	3.5k	0.825
1	4k	0.75
1	5k	0.65
1	5.8k	0.6
1	6k	0.525

Table 9 Band Pass Filter

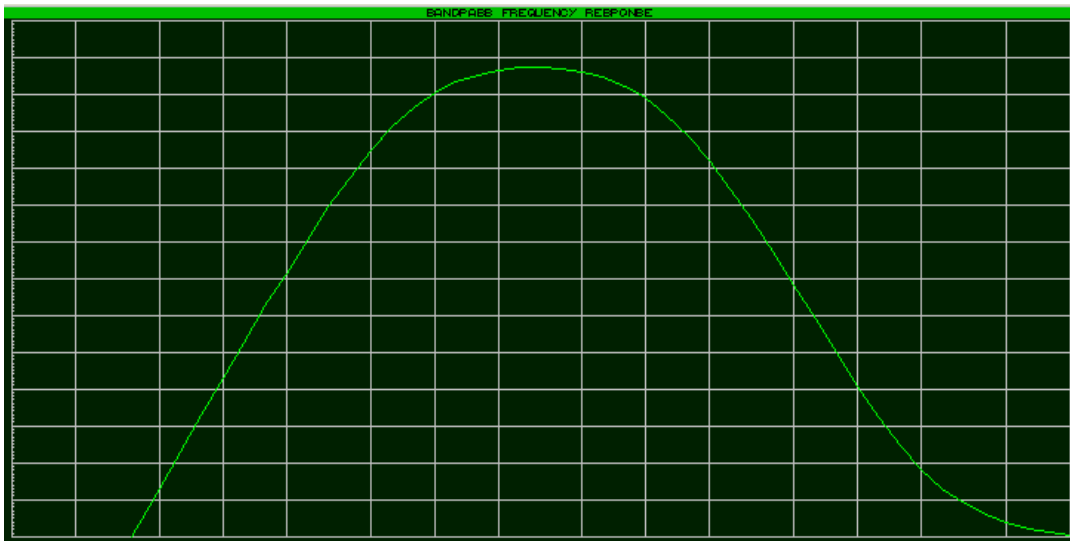


Figure 23 Band Pass Filter Frequency Response

HIGH-PASS FILTER

The following results were obtained for the unity gain high pass filter with a cut-off frequency of 5.8 kHz.

Signal Amplitude, V(peak)	Signal Frequency, Hz	Output Amplitude, V(peak)
1	5.8k	0.5
1	6k	0.525
1	7k	0.6
1	8k	0.65
1	9k	0.7
1	10k	0.75

1	12k	0.8
1	14k	0.85
1	16k	0.875
1	18k	0.9
1	20k	0.925
1	30k	0.95
1	50k	0.975

Table 10 High Pass Filter Frequency Response

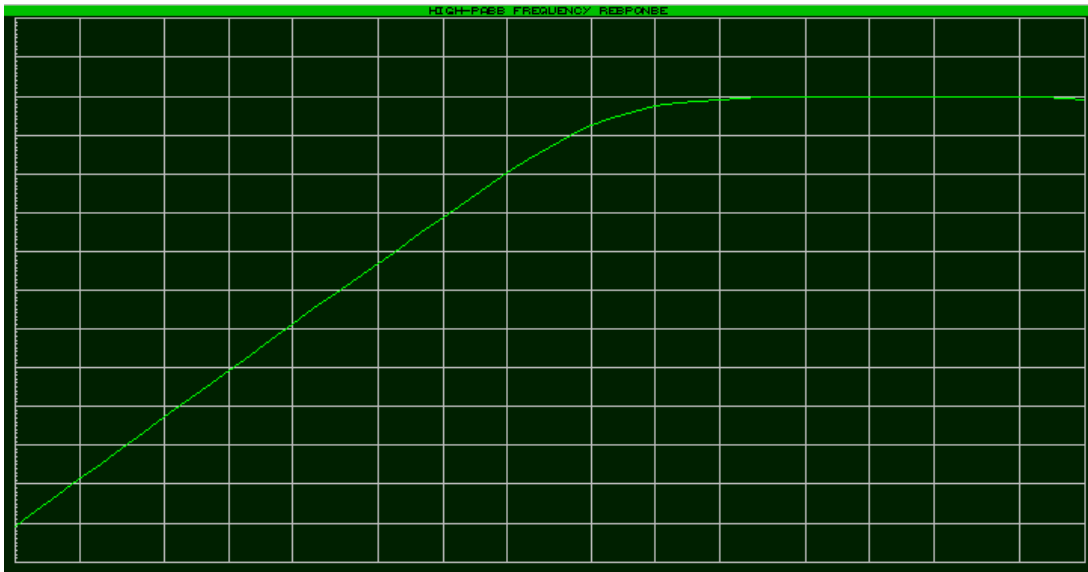


Figure 24 High Pass Filter Frequency Response

3-WAY FILTER FREQUENCY RESPONSE

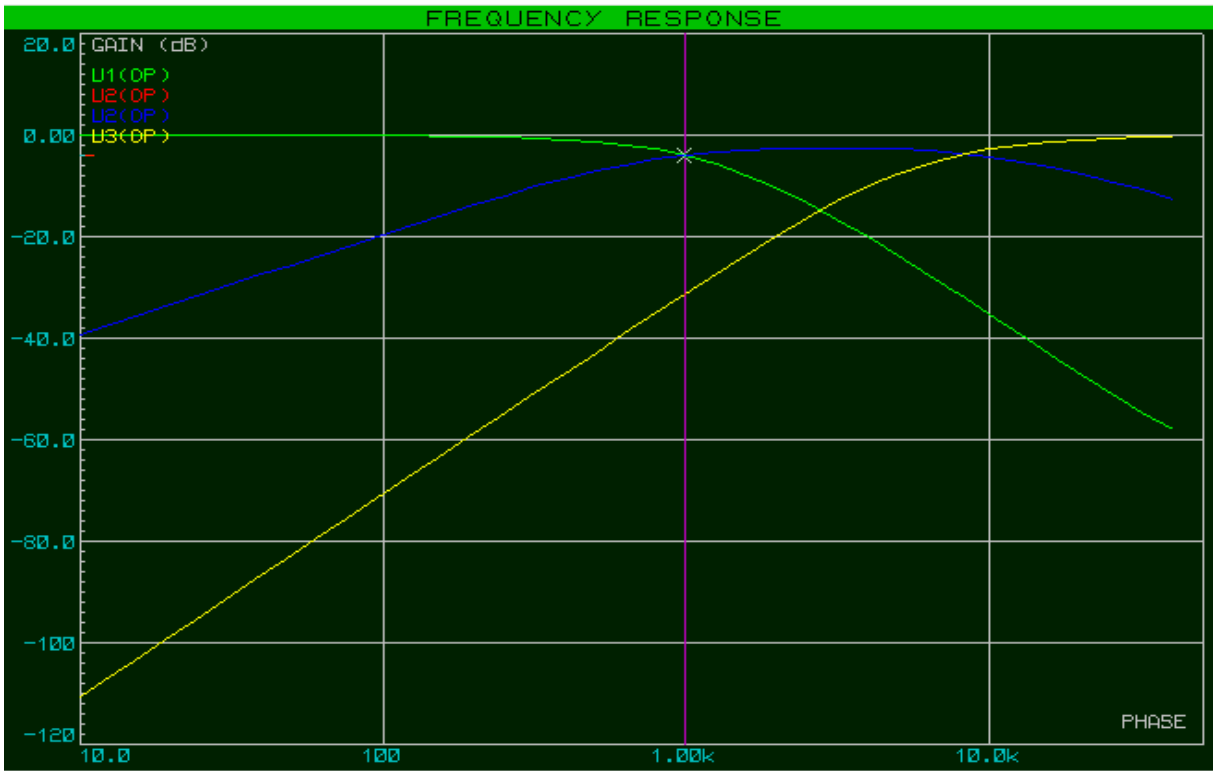


Figure 25 3-way Active filter frequency response

CHAPTER 5

5.1 DISCUSSION

The 100 watt power amplifier with a Darlington complementary output transistor was simulated and eventually fabricated on a Printed Circuit Board. As explained in the project, a 3-way active filter was designed to produce output at different frequencies.

The measured power 96.18 Watts was close to our expected value. For the active filters, the experimental results differ a bit from the simulated results when the two gain responses of each network are compared. This is because some of the components used in the circuit are not the exact values of the simulation components and moreover, some of them were rounded off to the nearest standard value. Component tolerance could also be a cause of the difference as they are about 5% and above.

The graphical results above show fairly similar performances of each of the crossover networks. The low pass and high pass filters show a unity gain over the pass-band up until the cutoff frequency.

5.2 CONCLUSION

The main objectives of this project were to come up with a 100watts power amplifier with a Darlington complementary symmetry output power transistors for use in a 3-way active crossover network. That is:-

- A 100W power amplifier with Darlington complementary symmetry output transistor
- Design a 3-way active crossover network consisting of a high-pass, band-pass, and a low-pass filter
- Test the complete power amplifier built and verify it works.

These objectives were met and the designs were implemented through simulation and breadboard testing before final fabrication of components on the printed circuit board (PCB). The audio output of the power amplifier was of high quality with minimal distortion since each filter drove its own specified frequency band hence producing the best sound quality on the basis of their capability.

The experimental errors of the project were at a minimal since before soldering components on the PCB, test was done through simulation using the Proteus 8.1 software. After the simulation, to further reduce any remaining errors, the components were placed on a breadboard and tested in the laboratory and the results obtained for both simulation and testing were tabulated in the results section of chapter four.

5.3 RECOMMENDATION

The Darlington complementary transistors, TIP33C and TIP34C used in the output of the amplifier produced high current which caused high power dissipation that damaged the transistors hence I would recommend use of a large heat sink to conduct the heat.

The use of other power transistors with less power could also solve the overheating while also paralleling of the Darlington power transistors to share the high current could also solve the high current problem.

Further improvement is required to achieve the objective of this project. The design should be modified to reduce the size of the circuitry through the use of integrated circuits (IC) on the input and voltage amplification stage.

REFERENCES

1. Handbook for Sound Engineers, Edited by Glen Ballou
2. Basic Electricity and Electronics, 4th Edition
3. Designing of Audio Power Amplifiers by Bob Cordell
4. www.futureelectronics.com/en/transistors/darlington-transistors.aspx
5. www.learnabout-electronics.org
6. FEE 302 Analog Electronics Class notes by Dr. Kamucha
7. Power Electronics Handbook – Rashid
8. M. E. Meserve, "Band-Pass Active Filter Designer," *Band-Pass Active Filter Designer*, p. 5.
9. JJC, "Active Filter Design (Sallen-Key Filter)," *Electrical Engineering Junior Lab*, p. 8, 9/7/02.
10. A.B. Williams, *Electronic Filter Design Handbook*, McGraw-Hill, 1981.
11. H. Zumbahlen, *Passive and Active Filtering*, Analog Devices.
12. S. P. Laboratory, *Analog Electronics, Active Filters*, CALIFORNIA: CALIFORNIA INSTITUTE OF TECHNOLOGY, Revision December 2012.

APPENDICES

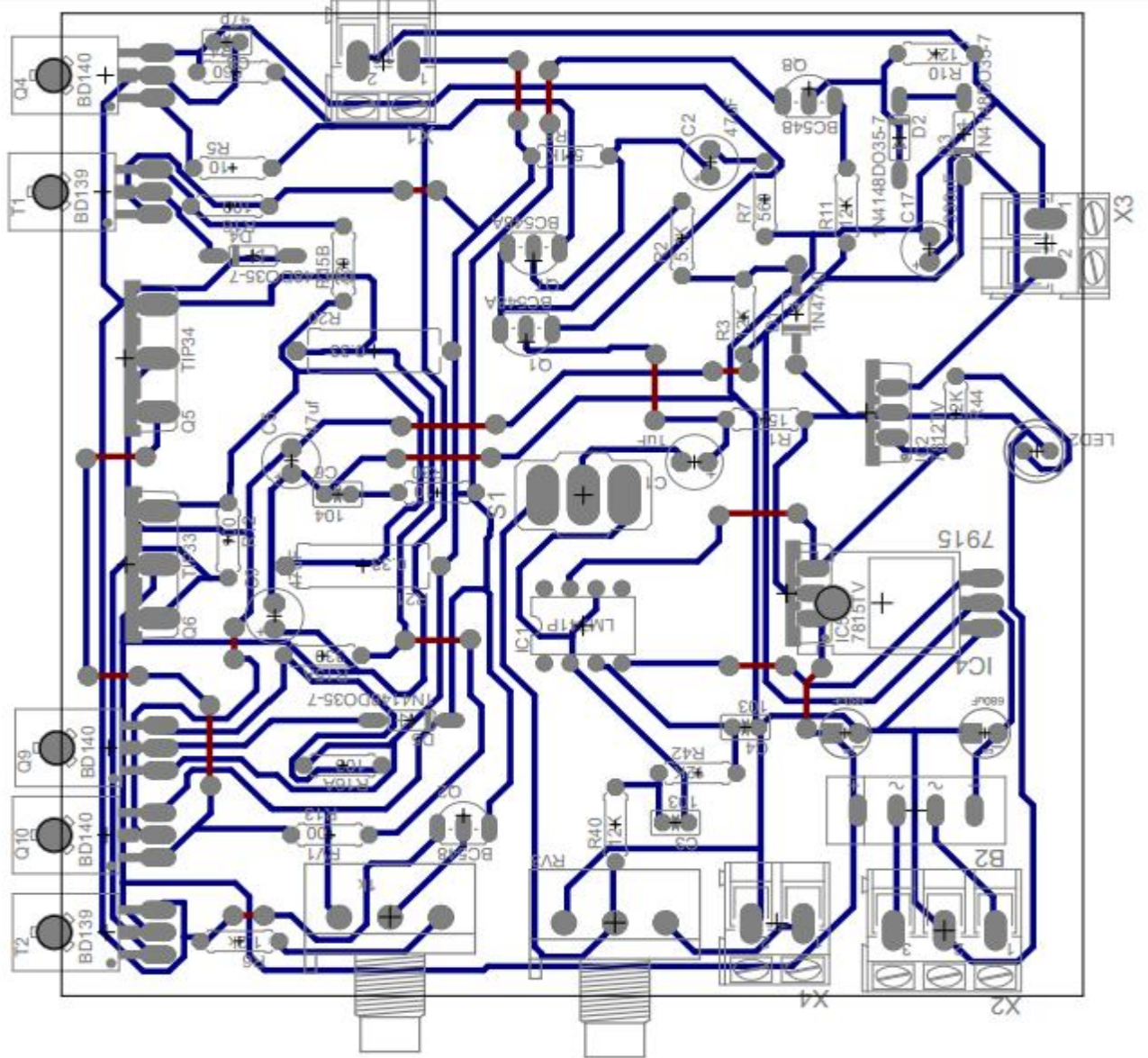


Figure 26 circuit PCB layout

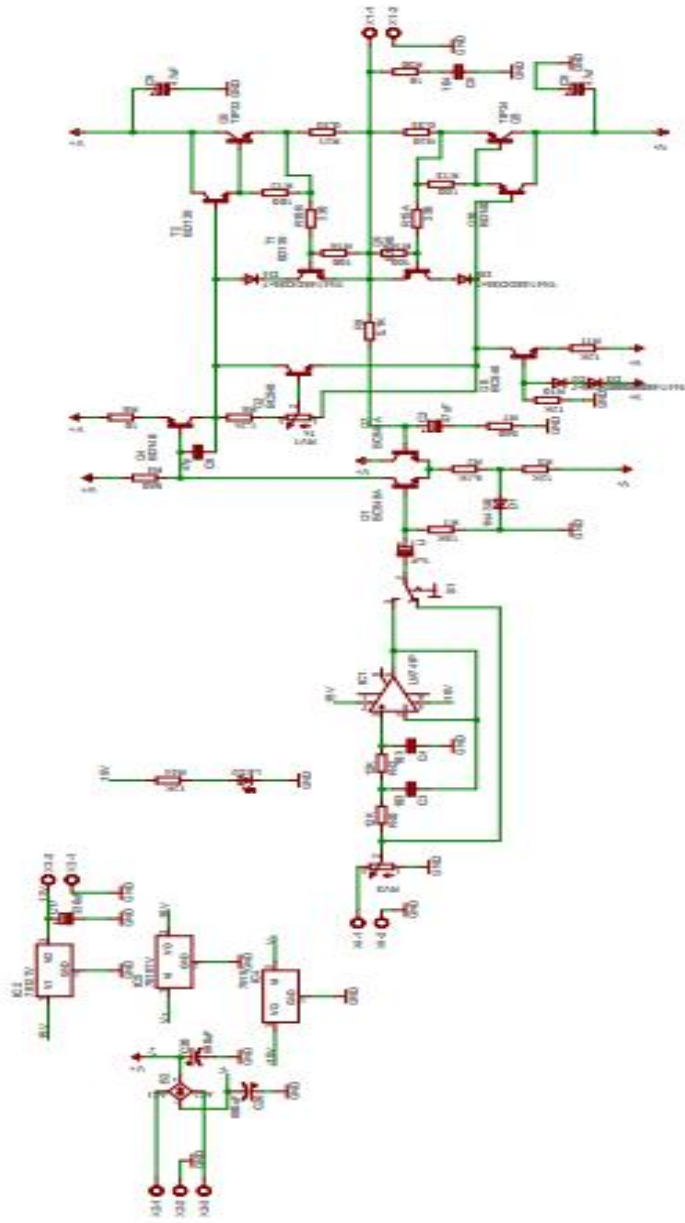


Figure 27 Circuit Design