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Induction Annealing of Small Ammunition Cartridges

by

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Project (E) 448

Report submitted in partial fulfilment of the requirements of the module Project (E) 448 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at the University of Stellenbosch

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June 2019

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Abstract

The aim of this project was to develop and build an induction circuit capable of annealing small ammunitions. Annealing is the process of heating metal in order to reduce hardness and increase ductility. This can be used to reverse the effects of strain hardening that occurs to gun cartridges when fired. The cartridges used in ammunition undergo strain hardening, which gets progressively worse with repeated use. Eventually this causes strain fractures in the brass cartridge. The process of annealing allows the grains in the brass cartridge to realign. This not only increases the longevity of the cartridge, but also improves accuracy by making the neck tension of the cartridge uniform

The report includes theory, design decisions, simulations, building of the circuit and a section for results. The success of the project was discussed in a conclusion and recommendations were made to further improve the system.

Uittreksel

In hierdie verslag is 'n stelsel geskep en beskryf om 'n induksie stroombaan te bou wat in staat sal wees om klein ammunisie te ontgloei. Analering is die proses van verhitting van metaal om die hardheid te verminder en die buigbaarheid te verhoog. Dit kan gebruik word om die effekte van spanning verharding wat by die geweerpatroon omhulsel voorkom, te keer wanneer dit afgedank word. Die patrone wat in ammunisie gebruik word, ondergaan spanning verharding, wat geleidelik erger raak met herhaalde gebruik. Uiteindelik veroorsaak dit breukfrakture in die koperpatroon. Die proses van ontgloeiing laat die korrels in die koperpatroon toe om te herstel. Dit verhoog nie net die langleeftyd van die patroon nie, maar verbeter ook die akkuraatheid deur die nekspanning van die patroonuniform te maak.

Die verslag sluit in teorie, ontwerpbesluite, simulasies, die bou van die kring en 'n afdeling vir resultate. Die sukses van die projek is in 'n gevolgtrekking bespreek en aanbevelings is gemaak om die stelsel verder te verbeter.

Acknowledgements

I would like to thank Dr.A Rix for the guidance provided throughout the project

I wish to thank both my parents for the continued support throughout my time at Stellenbosch University.

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Abbreviations

AC Alternating Current

ADC Analog to digital Converter

DC Direct Current

ESR Equivalent Series Resistance

FFT Fast Fourier

f Frequency

g Gram

IC Integrated Circuit

I Current

J Joule

K Kelvin

MOSFET Metal Oxide Semiconductor Field-Effect Transistor

PCB Printed Circuit Board

PLL Phase-Locked Loop

P Power

Q Qaulity Factor

R Resistance

SMPS Switch Mode Power Supply

VAC Voltage-Alternating Current

V Voltage

W Watt

ZCS Zero Current Switching

ZVS Zero Voltage Switching

2 Introduction

The cartridge of a bullet when fired is under immense pressure. When the smokeless powder is ignited the pressure within the chamber of the cartridge causes the outer wall of the chamber to expand. This creates a seal between the cartridge and the barrel of the gun. [1] This mechanism protects the user from the hot gas being expelled out of the barrel.

The immense pressure of the firing process work hardens the brass.[2] This causes the crystalline structure of the brass to deform and eventually fracture. The annealing process prevents this as the crystalline structure of the brass re-aligns itself when heated.

Annealing of cartridges was previously done by rotating the cartridge over the flame of a propane torch, but induction annealers have become more popular in recent years. Induction annealing is more efficient that traditional gas annealing.

Induction annealing works by creating an alternating magnetic field. The alternating field induces eddy currents within the cartridge.This creates heat due to the Joule effect. The greater the magnetic field created the greater the current in the cartridge and the faster the cartridge will increase in temperature.

As the neck of the cartridge is annealed this reduces the neck tension and helps improve accuracy. Annealing is however not done to the entire cartridge as this can cause safety concerns if the brass becomes too soft.

2.1 Problem Statement

The most common method used for the annealing is by rotating the cartridge in the flame of a propane torch. This is an inefficient way of annealing the neck of the cartridges as energy is lost to the surroundings as the cartridge is rotated. There is less control as the entire surface circumference of the cartridge is not being heated simultaneously.. This makes it more difficult to create neck tension that is uniform. The final problem with this method is the risk it poses by making use of an open flame from a propane torch as objects are more likely to catch alight plus the risk of propane gas leaking from the tank.

The other methods used are significantly worse. For example placing cartridges that are half full of water into an oven. This is inefficient as energy is wasted heating up the oven and the water in the cartridge. It is also very difficult to control what portion of the cartridge you anneal as the water evaporates, which can result in the body of the cartridge becoming too soft, causing it to break when fired.

2.2 Project Objectives

The problem under consideration is designing a circuit that will be able to produce a sufficient alternating magnetic field to heat the neck of a cartridge casing to its annealing temperature in a short enough time frame, so as to increase the ductility of the neck and shoulders of the brass but not weaken or affect the integrity of the rest of the cartridge casing.

The first objective of the project was to understand how annealing works, as well as factors that affect the process.

The second objective was to design and build a circuit capable of bringing a cartridge neck to its annealing temperature within 10 seconds, and preventing cartridge weakening. Furthermore the circuit should be operated from a main power supply and controlled using an IC.

2.3 Scope

This study specifically investigates the use of induction heating on small cartridges. It does not take into account other methods such as annealing using gas.

It specifically takes into account the annealing of a .308 cartridge. Cartridges with varying wall thickness as well as longer necks will require different annealing times.

Furthermore slight variations in factory pre-annealing and in metal content, amongst others, could also affect annealing times

A single ammunition casing purchased from one supplier, was used for the purpose of this assignment. Hence, the report did not consider any other factors that could affect the annealing process of different makes or suppliers of .308 ammunition.

2.4 Overview of Report

The report follows the following structure:

Chapter 3 details the literature study that was done to determine the effect of the annealing process on brass. It was also used to determine the inductance of the coil that would be required to anneal the brass within the specified time period.

Chapter 4 details the design and choices that were made to complete the annealing system

Chapter 5 details the software design of the system.

Chapter 6 details the results of the project.

Chapter 7 provides a conclusion for the project.

Chapter 8 provides future design recommendations for the project.

3 Literature Study

This literature study was conducted in order to understand the affect of annealing on brass cartridges. Also to determine the process that would have to be used in order to heat the cartridge to the specific temperature within the required amount of time.

3.1 Effect of Annealing on Brass

When brass is deformed it will return to its original form if the stress is removed from the metal before it reaches its yield point. Although the metal has returned to its original shape the molecular structure of the metal changes.[3] The stress introduces faults within the crystalline structure of the material. During applied stress the crystalline structure forms grains that are separated by boundaries as well as slip planes. As the number of slip planes increase they become entangled, the internal stress of the material increases which in turn increases the hardness and brittleness of the material.[4] This is known as strain hardening or work-hardening.

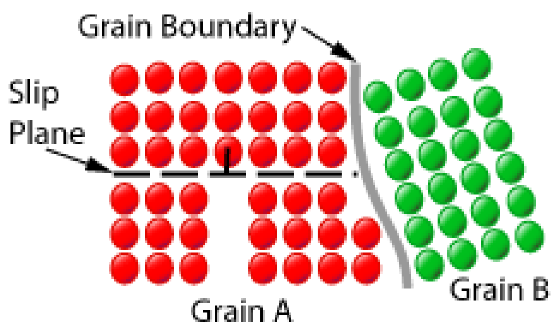

Figure 1: Grain Boundary [5]

This regularly happens to a brass cartridge when it is fired. Particularly to the neck and shoulders of the cartridge as the barrel cannot restrict its deformation. Repeated reuse of cartridges causes them to strain harden and fracture. As seen in Figure 2, while the brass may not fracture before it reaches its yield point, it will not return to its original shape when the stress is removed.

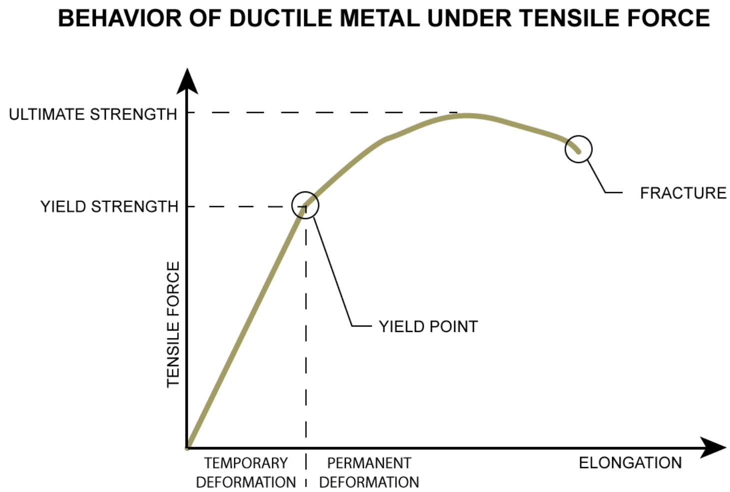

Figure 2: Grain Boundary [2]

The internal stress can be removed by heating the metal. Heating the metal excites the atoms in the structure. This allows the atoms to move which removes the strain within the brass. Depending on the amount of energy applied to the brass it goes through three stages. First, recovery, in which the strain in the brass is reduced. Second, re-crystallization which allows new grains to be formed within the brass. This stage also softens the brass and increases its ductility. Finally, grain growth, in which the grains grow larger as shown in Figure 3. [5]

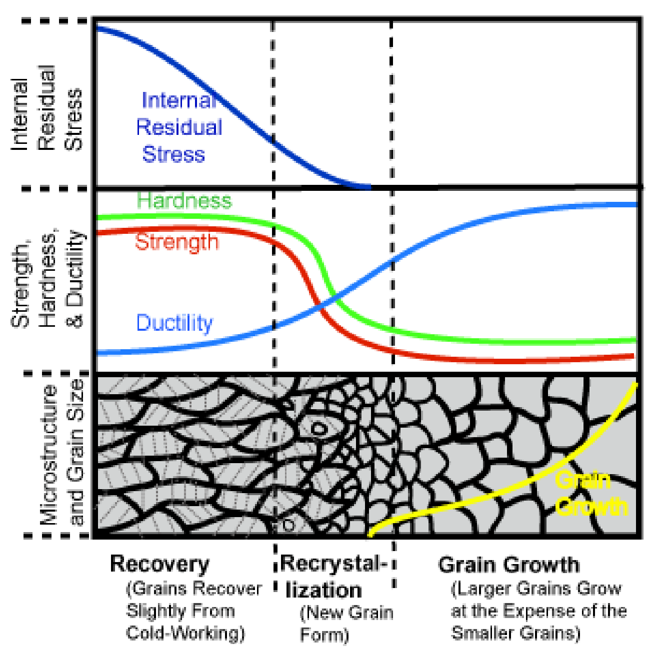

Figure 3: Recovery of brass during heating [5]

There is some disagreement with regards to the exact temperature to which brass should be heated, so that the casing is correctly annealed. This may be because if not heated sufficiently the internal strain on the neck of the cartridge is not reduced, but if overheated the cartridge becomes too soft. However the consensus is that the temperature should be between 400°C and 425°C. This project has chosen the higher boundary as the annealing temperature.

3.1.1 The Specific Cartridge

A single cartridge was chosen in order to standardize the energy required and the results. The .308 is one of the most common rifle ammunition's. It is a lightweight, powerful and accurate round and has been chosen as the cartridge that will be used during the testing phase because of its popularity and the fact that it is larger than some other popular ammunition types such as the 9mm, .22LR and the .223.[6] Larger ammunition requires more energy to reach annealing temperature, so if the prototype is capable of annealing the .308 it will be capable of annealing the other smaller cartridges.[7]

3.2 The Process of induction heating

Induction heating works by driving an alternating current through a transformer. The alternating current generates a magnetic field around the transformer. According to Faraday's Law, if a secondary conductor is placed inside the magnetic field of the primary transformer, eddy currents are induced in the conductor as seen in Figure 4.[8]. The cartridge is considered as the secondary transformer for the purposes of this project.

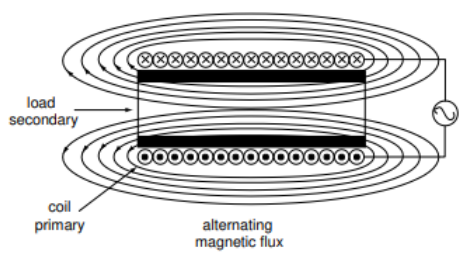

Figure 4: Principal behind Induction Heating [9]

As seen in Figure 4 the magnetic field formed around the coil can be calculated using Amperes Law.

$$Hdl = Ni = F \tag{1}$$

Where,
H is the strength of the magnetic field
dl is change in length of the coil
N is the number of turns in the coil.
i is the current in the coil.

Joules Law states the amount of heat produced is a function of the current and resistance. The heat generated is a result of electrons colliding with the atoms in the cartridge.[10] The heating of the material is thus directly related to the resistivity of the material. Joule's Law states that the heat increase is directly related to the power. [11]

$$P = I^2R \tag{2}$$

The specific heat formula from thermodynamics to calculate the overall power that will be needed to anneal the neck of the cartridge.[12]

$$Q = mc\Delta T \tag{3}$$

Where,
Q is the heat required [J]
m is the mass of the material [g]
c is the specific heat capacity of the material
ΔT is the change in temperature

The power transfer caused by the eddy currents thus needs to be considered, so that the power needed in the coil to produce sufficient eddy currents to heat the cartridge can be calculated. The eddy currents can be calculated by using equation 4. [13]

$$P_{\mathrm{T}} = \frac{\pi^3 l d^4 B^2 f^2}{8\rho} \tag{4}$$

Where,
l is the length of the conductor.
d is the diameter of the conductor
ρ is the resistivity of the material
B is the flux density of the magnetic field.

The above information can be used to calculate the effect that a single wound coil will have on the cartridge, however there are a few inductive heating effects that should be considered as well. When designing an inductive heater these include magnetic concentrators and the Skin effect.

3.2.1 Magnetic Concentrators

A magnetic concentrator is a ferrous material that increases the flux density of the coil. Having a high linearity and a low hysteresis. This can be used to concentrate the eddy currents in a small area of the core.

This concentration improves the efficiency of the coil as there is less fringing and a better coupling between the coil and the cartridge. This can be achieved by creating a small slit slightly larger than the diameter of the cartridge. This allows the magnetic field to have a higher intensity around the neck of the cartridge.

While this method can be used if the coil becomes saturated, the current through the inductor will become distorted, and the coil will no longer work effectively. The exact saturation limit of a coil is difficult to calculate and is better determined by measuring it practically. [14]

3.3 Skin Effect

The skin effect is the distribution of AC current across a conductor. The current density is the greatest at the external surface of the conductor and decays as you approach the centre.

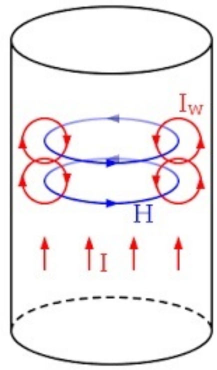

Figure 5: Skin Effect [15]

As shown in Figure 5 the current I creates the magnetic field H, indicated by the blue rings. The magnetic field then creates a current which opposes the flow of I. This current is indicated by I_w and the red rings. This phenomenon can be explained using Faradays Law which states:

$$\varepsilon = \frac{d\Phi}{dt} \tag{5}$$

Where,
ε is the electromotive force produced.
dΦ is the change in magnetic flux.
dt is the change in time.

$$d\Phi = d(BA) \tag{6}$$

Where,
B is the magnetic flux density
A is the Area.

$$B = \mu_0 \mu_r H = \frac{\mu_0 I}{2\pi r} \tag{7}$$

Where,
μ_0 is the permeability of free space.
μ_r is the permeability of the material.
H is the magnetic field strength.
I is the current in the conductor
r is the radius of the conductor

$$T = \frac{1}{f} \tag{8}$$

Equation 5 can be manipulated using 7, 6 and 8 into:

$$\frac{\varepsilon}{df} = \sqrt{\frac{\mu_{\mathrm{r}}}{2\pi r}} \frac{d\sqrt{HI}}{dt} \tag{9}$$

Equation 9 shows that change in frequency is inversely proportional to the square root of the current flowing through the inductor. Therefore, by increasing frequency you decrease the amount of current flowing through the inductor. In order to calculate the exact penetration depth the equation 10 can be used.

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \tag{10}$$

Where,
δ is the penetrating depth
f is the frequency of the AC current.
σ is the conductivity of the material. Which is $1.508e^7$
μ is the magnetic permeability of free space multiplied by the magnetic permeability of brass.
$\mu = \mu_{\mathrm{r}}\mu_0$

3.4 Oscillating Circuits

It is apparent that an oscillating circuit would be needed to drive a high frequency AC current through the work coil. There are a variety of methods capable of doing this. Theses methods were researched so that a decision could be made on the most practical choice.

3.4.1 Royer Oscillator

The Royer oscillator is a push-pull, DC to AC inverter that is commonly used in wireless power transfer and inductive heating. The Royer oscillator is unique as the oscillator can be driven by the DC input voltage . It works using the principal that the switches won't have identical characteristics. In practice the gates will not open at the same time. [16]

One of the transistors turns on before the other which results in a voltage across the primary winding. The current through one of the transistors creates a magnetic flux in the transformer. The magnetic flux creates a current in the fly back coil which closes the gate of the one transistor and opens the gate of the other. This process repeats itself creating an oscillating circuit. The Royer oscillator generally produces a square wave but by adding the capacitor and inductor as seen in Figure 6, the output becomes a sinusoidal wave. The addition of transistor Q3 allows the oscillator to be driven at different frequencies.

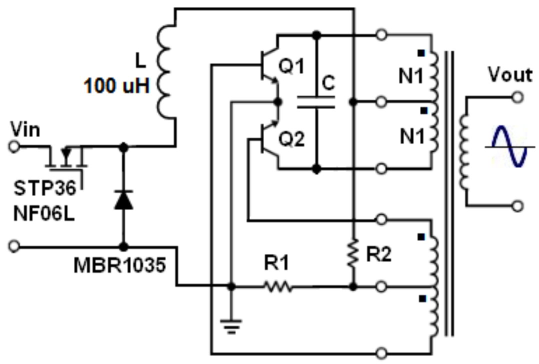

Figure 6: Modified Royer Oscillator [16]

3.4.1.1 Tank Oscillator

A tank circuit is a combination of an inductor and capacitor that produces oscillations of a desired frequency. The charged capacitors discharge into the inductors. Working on the principal that the inductor will not be able to allow the entire current to discharge instantly, the inductor will then discharge into the capacitor having the current flow in the same direction, however this will charge the opposite pole of the capacitor. This will change the overall direction of current flow. This process repeats creating oscillations in the circuit.[17]. It is important when choosing the capacitors for the tank circuit that the capacitors are non-polarized, have a low ESR and have the ability to operate at the chosen frequency.
The resonant frequency of the tank circuit is determined using equation 11. This is the point at which the reactance of the capacitors is equal to the reactance of the inductors in the circuit.[18]

$$f_{\mathrm{r}} = \frac{1}{2\pi\sqrt{LC}} \tag{11}$$

Where,
L is the inductance in Henrys
F is the Capacitance in Farads
$\mathrm{f_r}$ is the output frequency in Hertz

3.5 Driving Circuits

Both the tank oscillator and the Royer oscillator need to be driven at their fundamental frequency, to achieve their maximum power output. The Royer oscillator only requires a single transistor to be driven for the device to function at its fundamental frequency. The tank oscillator must be driven either using a half-bridge or an H-bridge driver. These were investigated so that the most ideal one could be chosen.

3.5.1 Half-bridge

Half-bridge inverters, commonly called two-quadrant circuits are typically connected as seen in Figure 11 and can be used to create an AC signal by switching the gates of the transistors inversely. For half-bridge circuits it is essential that dead time is added into the switching frequency to prevent the transistors being on at the same time. Having both of the gates on at the same time causes shoot through where in the DC source will be shorted to ground through the transistors.

Using a half bridge circuit allows limited control of the current going through the load. It only allows a positive voltage to be connected across the load and operation in one direction. The output of the circuit is a square wave with harmonics. This can however be converted into a sine wave using, three RC circuits in series. A sinusoidal wave is preferable as it supplies constant power throughout its operation.[19]

3.5.2 H-bridge

H-bridge converters are commonly called four-quadrant converters. They provide the user with more control as they allow the current to be reversed through the circuit. These are commonly used in motor drivers to enable the motor to be driven in both directions.

The H-bridge also produces a square output wave across the load, however the principal mentioned in section 3.5.1 can be reused to resolve this.

3.5.3 AC-DC conversion

The mains power needs to be converted to DC to power the oscillating circuits. There are a variety of ways to do this and these have been investigated.

3.5.3.1 Half-bridge Rectifier

Half-bridge rectifiers are the simplest form of rectifier circuit. It makes use of diodes to block out the negative portion of the signal. This is an inefficient method of power transfer as the load will only be provided with power every half cycle.

Large smoothing capacitors can be added across the output of the circuit to try and maintain a constant DC output however, there would still be a large voltage fluctuation between the peaks. The size of the smoothing capacitor is dependent on the load impedance as, a lower load impedance draws more current causing the capacitor to discharge more quickly.[20]

3.5.3.2 Full-bridge Rectifier

The full bridge rectifier operates in the same way as the half-bridge rectifier but allows both the positive and negative half cycle through. This is advantageous as power is applied to the load more frequently.

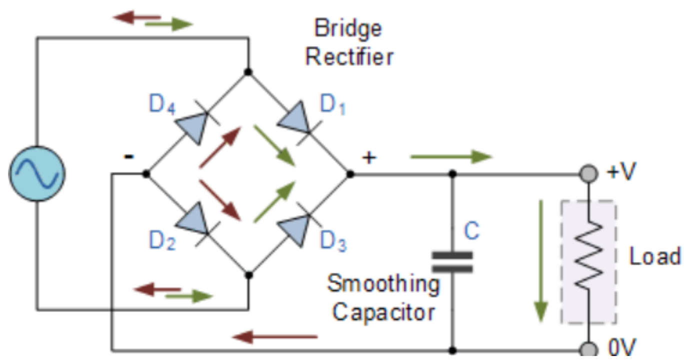

Figure 7: Topology of a Full-bridge Rectifier [20]

As in the half-bridge rectifier, smoothing capacitors can be added to reduce the ripple. By having the power applied twice as frequently it also allows the signal to be smoothed more easily as there is a shorter time period between the peaks. The effects of adding smoothing capacitors to the rectifier can be seen in Figure 8. It should also be noted that the voltage across the output of a full-bridge rectifier will be higher than a half bridge rectifier The average output voltage is also higher than a half wave.[20]

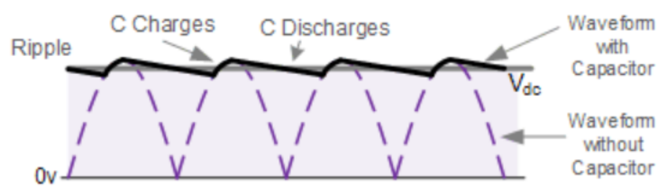

Figure 8: Comparison showing the effects of smoothing capacitors on a rectified AC signal [20]

3.5.3.3 Full-bridge Centre Tapped Rectifier

A full-bridge centre tapped rectifier makes use of a centre tapped transformer as seen in Figure 9. This circuit provides the same advantages as the normal full bridge rectifier, but allows the voltage to be stepped up or down by varying the winding ratio on the transformer.

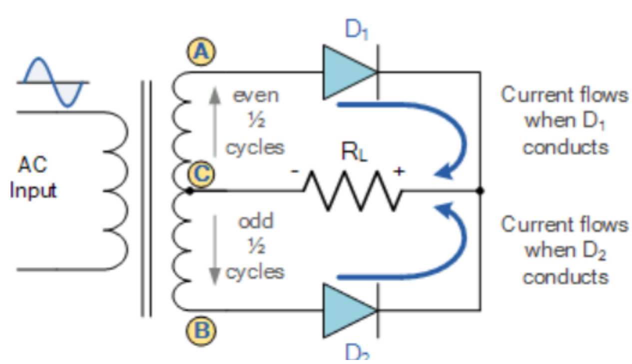

Figure 9: Topology of a Full-bridge Centre Tapped Rectifier [20]

4 Hardware Design

The information gathered in the literature study provided a guideline for the elements that had to be designed for the completion of this project. Figure 10 provides an outline of the various elements considered when the circuit was designed.

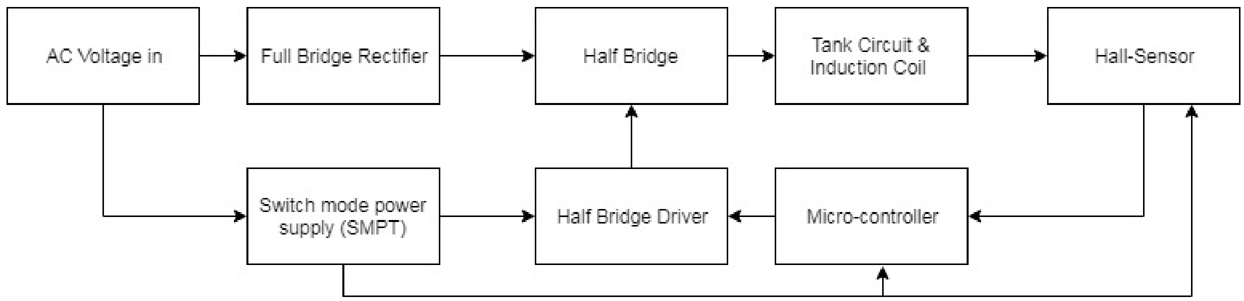

Figure 10: System Overview

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4.1 Work Coil Design

To design the work coil the amount of energy required must first be calculated. The .308 cartridge cases were cut 4mm below the neck along the manufactures annealing line. They weighed approximately 3g. Using equation 3. Brass needs to be heated to 673.15 Kelvin for the annealing process to be effective. Brass has a thermal capacity constant of $0.38\frac{JK}{g}$.

$$3 \cdot (673.15 - 298.15) \cdot 0.38 = 427.5J \tag{12}$$

The work coil needs to provide 427.5 J of energy to raise the brasses temperature to its annealing point. From this we can calculate the power needed to be produced by the work coil using equation 13. Using an annealing time of 10s.

$$Power = \frac{Joules}{Time} \tag{13}$$

$$Power = \frac{427.5}{10}$$

$$Power = 42.75W$$

The work coil therefore, needs to have a minimum of 42.75W in order to anneal the bullet within 10 seconds.

From the literature study, increasing the frequency increases the flux density of the magnetic field which improves the rate at which the bullet heats up. This indicates that the highest possible frequency must be chosen. Taking the skin effect into account it was determined that the frequency, with the penetrating depth the same as the wall thickness of the cartridge (36mm), was 1.4 KHz. This is incredibly low and will not provide a dense enough magnetic field to heat the brass. The operating frequency of commercially available annealing machines typically operate at 100KHz. It was decided that this frequency would be used but the PCB would have extra capacitor slots so that the frequency could be varied. The penetrating depth was calculated using equation 10

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}}$$

$$\delta = \frac{1}{\sqrt{\pi \cdot 100 \cdot 10^{-3} \cdot 0.7 \cdot 10^{-3} \cdot 4\pi \cdot 10^{-7}}}$$

$$\delta = 0.042mm$$

Although the bullet cartridge is thicker and the current will only be distributed on the surface of the wall, the high thermal conductivity of brass will ensure that the brass is still completely annealed.

Using the dimensions of a .308 cartridge, a work coil was designed with a marginally larger diameter than the cartridge as can be seen in appendix E.3. The work coil is longer than the area that must be annealed but was designed as such, so that more turns could be accommodated. This increases the inductance of the work coil, which in turn allows the current needed to heat the cartridge to be reduced. The work coil was designed with an inside radius of 1cm and 15 turns. It was constructed using a copper wire that had a 1.5mm diameter resulting in the length of the work coil being 4.6cm Using equation 14 the inductance was calculated.

$$L = \frac{\mu_{\mathrm{r}} \mu_0 N^2 \pi r^2}{length} \tag{14}$$

$$L = 1.68\mu H$$

The inductance of the work coil was measured to be 1.45μH which is lower than the calculated value but still within a reasonable range. The inductance of the work coil in conjunction with the power needed, can be used to calculate the magnetic field density required using equation 4 .

$$B = \sqrt{\frac{P_{\mathrm{T}} 8\rho}{\pi^3 l d^4 f^2}} \tag{15}$$

$$B = \sqrt{\frac{42.75 \cdot 8 \cdot \cdot 4\pi \cdot 10^{-7}}{\pi^3 \cdot 0.04 \cdot 0.02^4 \cdot 100000^2}}$$

$$B = 465.37\mu T$$

This equation does not take into account the power loss in the work coil and the fact that the magnetic field will not be perfectly coupled with that of the cartridge. Then by using the magnetic field density the current required in the coil can be calculated using equation 16 . This calculation was done assuming that the cartridge couples perfectly with 5 of the turns.

$$I = \frac{Bl}{N\mu_{\mathrm{r}}\mu_0} \tag{16}$$

$$I = \frac{465.37 \cdot 10^{-6} \cdot 0.04}{5 \cdot 4\pi \cdot 10{-}7}$$

$$I = 2.9624A$$

The current can now be used to calculate the power needed in the work coil to heat the cartridge, however this does not account for the power dissipation caused by the conduction of the work coil. The sum of these values will provide the overall power needed in the work coil. The losses in the work coil can be calculated using the measured inductance value.

$$P_{\mathrm{loss}} = I^2 j\omega L = 1.021W \tag{17}$$

This power loss is different from the eddy currents described above as eddy currents can be considered a power transfer as opposed to a loss. This loss will result directly in the work coil heating up, and while some of the energy may be transferred to the cartridge through radiation, it will be minimal and does not need to be accounted for. The sum of $\mathrm{P_t}$ and $\mathrm{P_{loss}}$ shows that the work coil must operate at 43.808W, not accounting for losses caused through radiation.

4.2 Half-bridge

It was decided that the half-bridge driver would be used in conjunction with the tank circuit to provide the AC current needed for the operation of the coil. Justification of these choices is discussed in the proceeding sections.

As seen in Figure 11 a half-bridge converter also known as a two-quadrant converter allows current to flow in both directions through the inductive load. This allows the DC current to be converted to an AC signal. The current will however only be operating in the positive region. A full-bridge rectifier could have also been used to drive the inductive load as it provides the ability to drive the current in both the positive and negative regions. This was considered unnecessary as there is no benefit in driving the current into the negative region for this particular application.

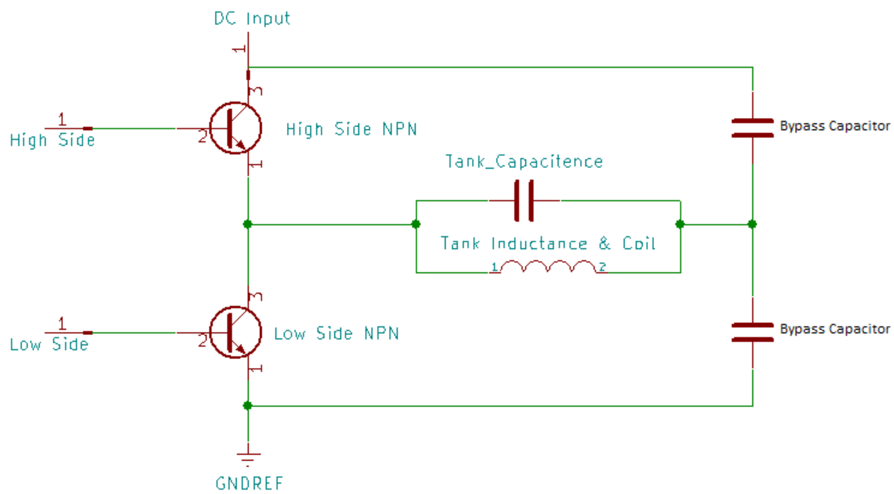

Figure 11: Half Bridge Current Flow

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Bypass capacitors chosen at 470F are connected between the power line (DC source) and the ground plane to remove stray inductance's on the DC path. [21]. These capacitors remove any possible DC offset that could be present across the-half bridge. The input voltage will be equally split over these capacitors. This allows these capacitors to have a lower rated voltage than the MOSFETs.

$$V_{\text{cap}} = \frac{V_{\text{d}}}{2} \tag{18}$$

Each capacitor will have a voltage of 150V. This allows these capacitors to have a lower rated voltage than the MOSFETs.

4.2.1 MOSFET Choice

Considering that MOSFETs are driven by a rectified wall voltage they have to be rated for a minimum of 325V, but due to the harmonics caused by the oscillating circuit and the transient voltages spikes that can be caused by switching from an inductive to capacitive load, it was decided that the MOSFETs should be rated for 500V. This will protect them from any unexpected transient voltage spikes. It was also decided that in the interest of decreasing the annealing time to under 10 seconds the MOSFETs were chosen to have a current rating of above 20A. The final MOSFETs that were chosen were the IXTQ26N50P, as they met the above criteria.

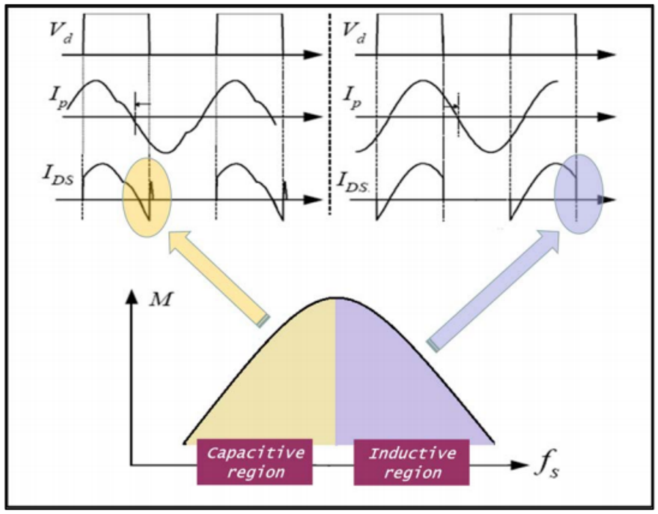

Figure 12: The effects of Capacitive loading versus Inductive loading [22]

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When being operated in the inductive region ZVS occurs across the MOSFETs with a positive current flowing from the drain to the source, however when operated in the capacitive region the MOSFETs switch during ZCS. This switches the current direction of the MOSFET causing the current to flow from the source to the drain.In Figure 12 the current reversal on the MOSFET can be clearly seen during capacitive switching. Figure 13 further shows the effects of current reversal on the resonant circuits output, causing the wave form to spike and distort.[22]

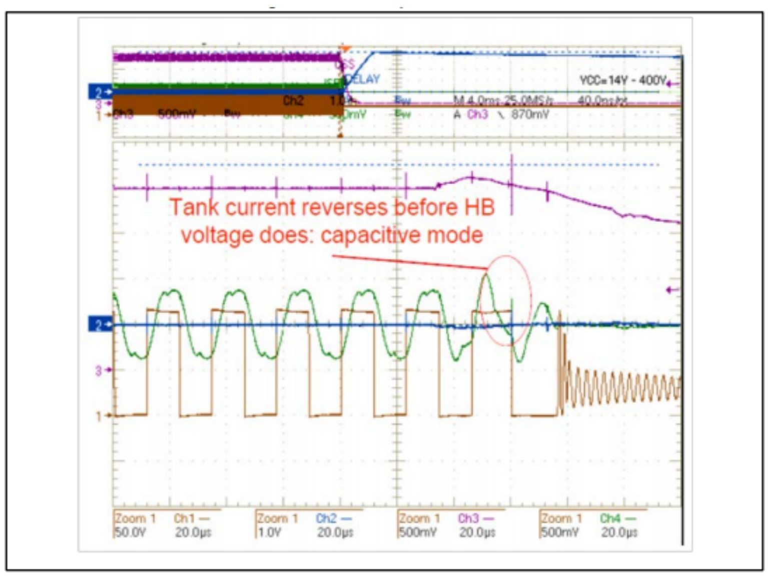

Figure 13: The effects of current reversal on the Sinusoidal output of the load [22]

.

To improve ZVS switching a fast body diode can be connected between the drain and the source of the MOSFET as this allows the energy in the MOSFET to be drained. ZVS also improves the efficiency of switching the MOSFETs by minimizing the losses that occur during hard switching. Hard switching occurs when there is an overlap between the current and the voltage waveforms. By removing this overlap and making use of soft switching, where the waveforms don't overlap, the efficiency of the switching is improved.[23]

When a MOSFET is switched the parasitic inductance's of the track and the drain terminal can cause a voltage surge between the source and drain terminals. This surge is then fed back into the gate of the MOSFET causing ringing. If the ringing is large enough it can cause the MOSFET to switch on and off until the ringing dissipates [24]. This can lead to the circuit being driven at the incorrect frequency and it can also cause shoot through on the half-bridge circuit. In order to dampen the effects of the ringing, a capacitor can be connected between the drain and the source of the MOSFET. A 1μF polyester capacitor was chosen to reduce the ringing. It is important to note that certain capacitors change relative to frequency which may make them unsuitable for this particular application.

A pull down resistor can also be added between the source and the gate of the MOSFET. When the MOSFET is turned off it is left floating. By adding in a pull down resistor you create a path where parasitic currents from the floating MOSFETs can discharge. This resistor needs to be large enough to minimize current discharging between the gate and the load.

4.2.1.1 MOSFET Losses

The losses in the MOSFET need to be calculated to see if a heat sink is required. The switching and conduction losses of the MOSFETs were calculated using LTSpice as this is generally more accurate than calculating the losses using circuit analysis. The sum of the losses P_D was 4.86W.

Using the thermal resistance model the heat dissipation was calculated without the use of heat sink

$$T_j = T_A + P_D(\theta_{j\text{-}A}) \tag{19}$$

Where,
T_j is the heat of the junction
$T_A = 25°$ is the ambient temperature
$P_D = 4.86$W the power that needs to be dissipated
$\theta_{j\text{-}A} = 40$ °/W the increase in temperature per watt.

$$T_j = 219.4°$$

This is well above the rated temperature of a 125°. A heat sink needs to be added to reduce the overall temperature of the cartridge.

$$T_j = T_A + P_D(\theta_{j\text{-}C} + \theta_{C\text{-}HS} + \theta_{HS\text{-}A}) \tag{20}$$

$$T_j = 25 + 4.86(0.2 + 0.3 + 1.5)$$

$$T_{\text{j}} = 34.72^{\circ}$$

This temperature is more than acceptable for operation. Two heat sinks were available with a thermal resistance of 1.5°/W which is why they were used. Practically smaller heat sinks should be used as the MOSFETs could be allowed to get hotter and they will be less expensive.

4.2.2 Full-bridge Rectifier

The diode full-bridge rectifier was chosen as it was decided that the voltage did not need to be stepped up or down as well as the fact that it would be easier to construct than the centre tapped rectifier. The half-bridge rectifier would have had a far higher ripple component, which undesirable when using a DC voltage.

It was decided that a full bridge rectifier would be used to provide the DC source for the inductive load. Rather than building a rectifier using individual diodes a GBPC3506W-G was used. The GBPC3506W-G provides 4 internal diodes connected in a standard full bridge configuration. A capacitor was used in parallel with the diode bridge in order to provide a smoother DC output.

$$V_{\text{ripple}} = \frac{I_{\text{load}}}{2fC} \tag{21}$$

where,
V_{ripple} is the peak size of the ripple voltage
I_{load} is the current being drawn by the load
Rearranging 21 allows us to calculate the required value of the smoothing capacitor.

$$C = \frac{I_{\text{load}}}{2fV_{\text{ripple}}} = \frac{20}{2 \cdot \cdot 100 \cdot 10^3 \cdot 8} = 12.5\mu F \tag{22}$$

From equation 22 it was decided that a 10μ F capacitor would be used. This was because a larger ripple voltage would have a minimal impact on the performance of the circuit.

4.2.3 Half-Bridge Driver

The high voltage MOSFETs seen in Figure 11 could not be driven using the output voltages of the STM32 due to their high gate turn on voltage of 10V-20V. It was decided that the voltage of the STM32 should be stepped up to 15V to accommodate the turn on voltage of the MOSFETs. The IR2184 was chosen as the gate driver as it not only steps up the input voltage from 5 to 15 volts but also provides a dead-time delay between 4μ - 6μ which will prevent shoot through during operation. Figure 14 provides an overview of the typical connection of the IR2184 [25].

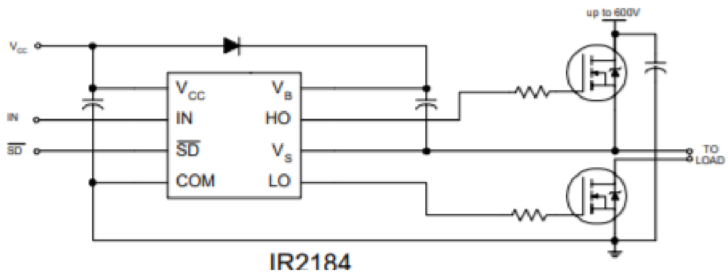

Figure 14: Typical Connection of IR2184 [25].

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A resistor needs be connected between the high and low side of the gate driver and the high and low side MOSFETs. These resistors are used to limit the current at the gate of the MOSFET. The resistor value typically varies between 10 Ω and 30 Ω, however they were set at 10 Ω to improve the switching speeds of the MOSFETs. As seen in Figure 15 this greatly increase the amplitude of the voltage spikes, however these can be reduced by using the design specifications for the capacitors shown above.

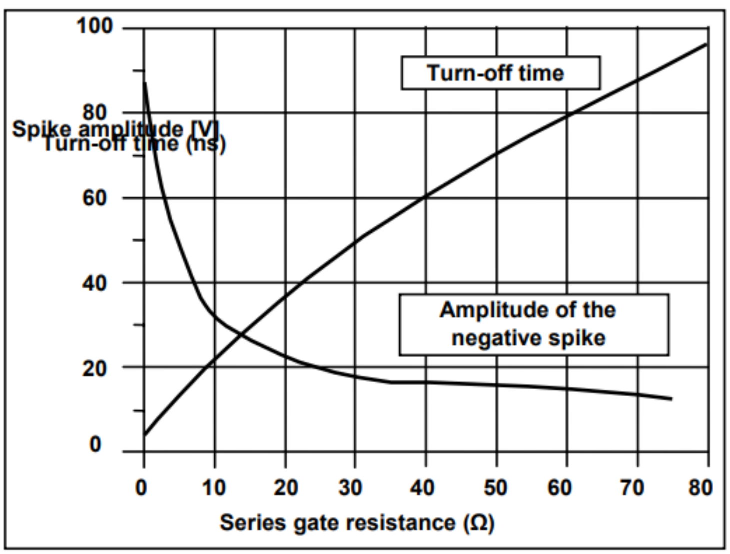


Figure 15: Series Gate Resistance vs. Amplitude of Negative Voltage Spikes and Turn-off time [21].

By adding a parallel diode across the gate resistor, the diode prevents the gate from opening in its off-state. By allowing the charge stored in the MOSFET gate to discharge through the diode, the diode improves the off time of the MOSFET but does increase the turn-on time which reduces the voltage spikes in V_s.[21]

4.2.3.1 Initial Current Limiter

The smoothing capacitors in the full bridge rectifier need to be charged up during turn on. Referred to as inrush current. This causes the current drawn during turn on to be several times higher than the current drawn during steady state operation. This can cause component damage as a current higher than rated will flow through. It can also cause the circuit breaker to trip if the inrush current is higher than its rated value.

To prevent this a resistor can be connected in parallel with a switch between the circuit and the power supply. When the switch is closed the resistor limits the amount of current that can flow into the circuit, forcing the capacitors and inductors to charge up more slowly, preventing damage to device components. Once the switch is turned on, the resistor can be bypassed allowing the device to draw the required current needed for steady state operation.

A fuse can also be connected between the device and power supply to protect the device even when the inrush current limiter is being bypassed during steady state operation.

4.2.3.2 Boot-Strap Power Supply

The bootstrap power supply (capacitor and diode in series) is an effective and low cost way of driving the high side MOSFET.The capacitor insures that the voltage across the gate is higher than the voltage at the source. [26]

The boot strap capacitor was calculated using equation 23. It should be noted that in the equation $I_{\mathrm{Cbs(leak)}}$ is only relevant if an electrolytic capacitor has been used. [21]

$$C \geq \frac{2[2Q_{\mathrm{q}} + \frac{I_{\mathrm{qhs(max)}}}{f} + Q_{\mathrm{is}} + \frac{I_{\mathrm{cbs(leak)}}}{f}]}{V_{\mathrm{cc}} - V_{\mathrm{f}} - V_{\mathrm{LS}} - V_{\mathrm{min}}} \tag{23}$$

Where,
Q_{q} =65nC -Gate Charge of High-Side MOSFET
f = 100Khz Frequency of operation
$I_{\mathrm{Cbs}_{\mathrm{(leak)}}}$ = 10 μA Bootstrap capacitor leakage current
$I_{\mathrm{qbs}_{\mathrm{(max)}}}$ = 150μA Maximum V_{BS} quiescent current
V_{cc} = 15V Logic section voltage source
V_{f} = 1.2V Forward voltage drop across the bootstrap diode
V_{LS} = 0 Voltage drop across low side FET or load
V_{min} = 10 Minimum voltage between V_{b} and V_{s}
Q_{is} = 5nC Level shift required per cycle[26]

From the above equation it was calculated that the value of the bootstrap capacitor had to be greater than or equal to 1.3μF, hence a capacitor of 10μF was chosen. A second low-ESR can be connected in parallel with the bootstrap capacitor to reduce overcharging caused by V_{s} undershoot.

A capacitor needs to be connected across V_{cc} and COM. This supports the recharging of the bootstrap capacitor and acts as the low side output buffer. It is recommended that this capacitor has a low-ESR and a value 10 times greater than the calculated C_{B} and was thus chosen as 221.3μF. [21]

4.3 Tank Circuit

The PCB was designed so that capacitors and inductors could be added or removed to not only change the oscillatory frequency but also to change the ratio between the inductors and capacitors as this changes the decay of the gain around the peak of the Bode plot. This would allow the design to accommodate the chosen 1.9μF series with the induction coil, as well as an additional 440nF which allows the frequency to be lowered.The value of the fundamental frequency was calculated as 97.5KHz using equation 24.
24

$$f_{\mathrm{r}} = \frac{1}{2\pi\sqrt{LC}} \tag{24}$$

A spice simulation was created using the chosen values above which yielded the Bode plot seen in Figure 16. The simulation behaved as expected and has a peak gain close to the originally chosen 100KHz and the calculated value.

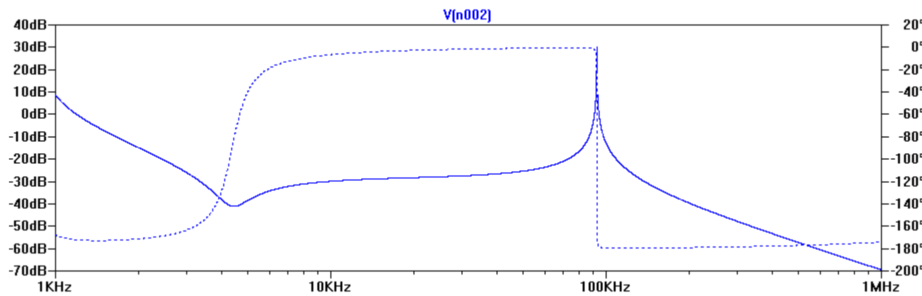


Figure 16: Simulated resonant frequency of the tank circuit

4.3.1 Inductor to limit current

An inductor must be placed between the output of the MOSFETs and the input of the tank circuit in order to limit the amount of current entering the circuit. This is because capacitors have a low impedance for high frequency signals, effectively making them short circuit. The effective impedance of the capacitors was calculated at 0.8Ω using equation 25. This low value causes a voltage across the tank circuit.

$$X_{\mathrm{c}} = \frac{1}{\omega C} \tag{25}$$

Where,
X_c is the impedance of the capacitor
When an inductor is wound around a core and a current is passed through it, it produces a magnetic flux in the core. The magnetic flux induced in the core causes a secondary voltage that resists the changes in electrical current in the indicator. Using equation 26.

$$V_{\mathrm{L}} = -L\frac{di}{dt} \tag{26}$$

Where,
V_L is the voltage drop across the inductor
L is the inductance of the coil.
di is the change in current of the coil.
dt is the change in time.

The difference in impedance between the current limiting inductor and the work coil will cause the voltage to be lower in the coil circuit than the supply. The ratio between impedances was used to calculate that the $V_{coil_{avg}}$ will be 11.4V

4.3.1.1 Quality Factor

Quality factor (Q) is a dimensionless unit that describes the damping of the circuit.[27] For a tank oscillator the quality factor Q can be described as the ratio of energy stored in the resonator to the energy supplied by the generator. The quality factor of a oscillatory tank circuit can be calculated using equation 27.

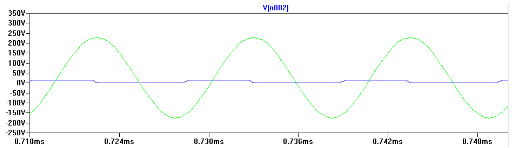
$$Q = R\sqrt{\frac{C}{L}} \tag{27}$$

Quality factor explains a variety of effects that occur in a resonant circuit. Increasing quality factor reduces the bandwidth of the oscillator, reducing phase noise which is the random shift in the phase of a signal and increases ringing with in the circuit which is the main component in a resonator Thus quality factor should be made as large as possible. This is done by increasing the capacitance value in the tank circuit.

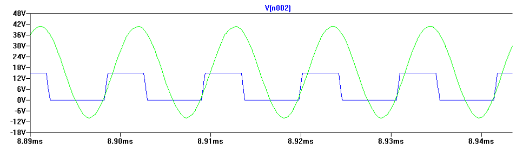
4.3.1.2 Maximizing Work Coil Power

Another way to maximize the power going into the load, is to operate as close as possible to the peak of the Bode plot. When you insert the cartridge into the work coil it changes the load being placed on the circuit which changes the oscillating frequency of the tank circuit. The oscillating frequency of the tank circuit will also begin to change as the cartridge begins to heat up due to the changing resistivity of the cartridge, this change is however very small and can be neglected for the purpose of this project. The driving frequency therefore needs to be changed in order to track the peak of the Bode plot to maximize power.

The phase difference between the high side MOSFET switching and the AC voltage in the work coil can also be used to track the difference. Achieving the highest power in the work coil occurs when the signals are 90 deg out of phase. The power gradually decrease's as the phase difference between the signals increases. Comparing Figures17a and 17b, the importance of driving the tank circuit at the correct frequency can be observed. There is a 3% deviation in the driving frequency between the two Figures, however this deviation caused an 87% reduction in the voltage.



(a) Driving at Bode Plot Peak



(b) Driving 3% below optimal frequency

Figure 17: Effect of a 3% variation of the driving frequency

It should be noted that when tracking the highest power in the circuit, the frequency should be adjusted from a higher to lower value to avoid the instability caused by captive loading. [28] The circuit should remain operating in the inductive region, because switching from an an inductive load to a captive load causes transient voltages that can damage certain circuit components

There are a variety of ways to maximize the load current in the work coil. The first would be to use a PLL. A PLL is a negative feedback loop coupled with a phase compactor and VCO. It allows the phase comparison and correction of two signals. Others are; shunt capacitors, Hall sensors and non-invasive current sensors, all of which allow the current to be measured on a particular point on the circuit. A Hall sensor was chosen for the prototyping of the board as it could be directly attached to the circuit board and the signal could be measured by the micro-controller.

4.3.1.3 Hall Sensor

The Hall sensor works using the Hall principle which states that when a current carrying metal strip is placed in a magnetic field, the positive and negative charges are pushed to opposing sides of the magnetic strip as shown in Figure 1. This creates a measurable voltage across the strip. As the strength of the magnetic field increases there is a larger build-up of positive and negative charges on either side of the strip increasing the voltage across it, to maximize the amount of current flowing through the load. [29]

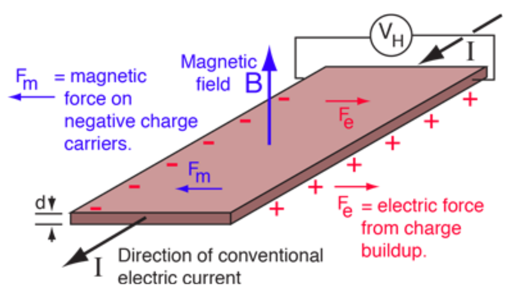


Figure 18: Hall Effect [29]

The ACS756SCA-050B-PFF-T was chosen for this particular project, as there is an electrical isolation between the tank circuit and the sensor. It has a low internal resistance and a high power tolerance. [30]. The typical connection of the device is shown in Figure 19. The device produces an analog output of $\frac{V_{cc}}{2}$. This value can vary between 3V and 8V. This output is connected to the ADC pin on the STM32 controller.

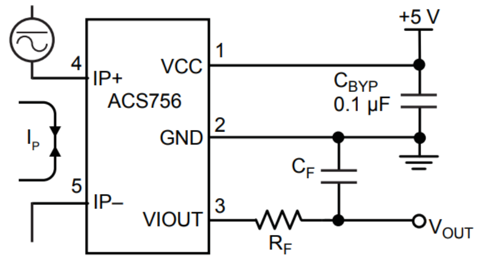


Figure 19: Typical Connection of hall sensor [30]

C_{BYP} was chosen to be 0.1μF as this was the suggested value. C_F was chosen at 10μF and R_F was chosen to be 100 because of the low output current and voltage.

4.4 5 and 15 Volt Power Supply

A 5 volt power is required to power both the STM32's. A further 15 volt power supply is also needed to power the Vcc of the IR2184 in order to drive the MOSFETs. In order to achieve this two zener diode voltage regulators were designed to provide the 15V Vcc. As seen in Figure 20, R_s is used to limit the current entering the circuit from the main DC supply. A zener diode is then connected between this resistor and ground to create a stable low ripple DC output voltage.

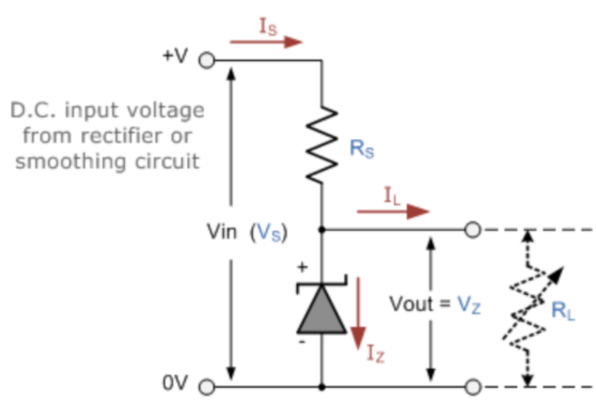


Figure 20: Typical Zener Diode voltage regulator [31]

The STM32 has a maximum current rating of 150mA and a typical operating range between 87mA and 109mA and the typical operating current of the IR2184 is 1mA. In order to limit the current entering the circuit $R_{s_{STM32}}$ was chosen to be 3.3K created by using 3 10K each with a 10W rating. The total power across each resistor will then be 9W for a total of 27W.

A second zener diode voltage regulator was designed to provide the 15V supply using a larger 330K resistor.

5 Software Design

The STM32 was chosen as the controller for this particular project, as it has a variety of on board functions, allowing greater versatility. It was also chosen as it has a clock speed that is capable of easily preforming all necessary tasks for this project.

5.1 Pulse width modulation

The STM32 makes use of of an internal clock counter (pre-scaler) and a repitition counter, so that it can generate a PWM signal. The pre-scaler can be considered the first divider as it divides the original clock speed of 72MHz. The repetition counter can then be used to further divide the clock speed. This information can be used to create an equation for the frequency of the PWM

$$f = \frac{\frac{InternalClock}{Prescaler}}{RepetitionCounter} \tag{28}$$

The value of the pre-scaler was chosen to be 0 for this particular project. A value of 0 is equivalent to a division of 1 providing the greatest resolution for changing the frequency. The repetition begins at 500 which provides a frequency of 144KHz. This limit was chosen as it is well above the fundamental frequency of the resonant circuit. The lower boundary was chosen at 738 as this provides a frequency of 97.4KHz. This frequency is above the frequency of the resonating circuit but was chosen because adding the load causes a negative phase shift. If the load is added after the control system has begun there is a possibility that the load will be shifted from being an inductive load to being a capacitive load which could potentially damage the circuit.

As well as providing the PWM signal for the MOSFET driver the STM32 is also used to provide the $\overline{SD}$ signal. The $\overline{SD}$ signal is a positive logic pin on the IR2184 and must be pulled up for the device to generate the appropriate output signal.

5.2 Voltage Sensing

Operating as close as possible to the resonant frequency of the oscillating circuit, improves efficiency and time required to heat the cartridge. The STM32 receives a voltage between 2.5 and 3.3 from the current sensor. This was originally converted to a current but as only the peak of the Bode plot had to be found it was deemed unnecessary.

The values are read into one of the ADC's on the STM32. These values are averaged in sets of five to allow for some noise compensation. The current value and the previous value are then compared and a shift in the respective direction is made.

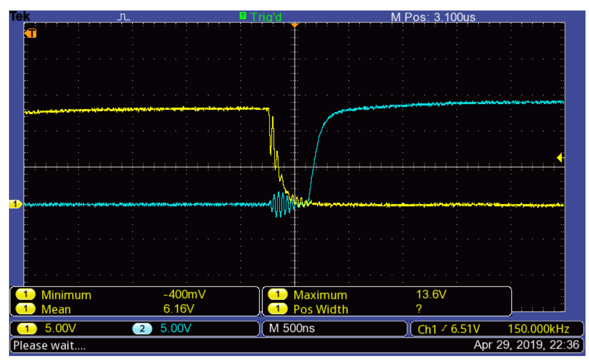
6 Results

It should be noted that that the tracks on the PCB were unable to dissipate enough heat which resulted in some of the tracks burning. This could have been fixed by widening the tracks on the PCB, but due to time constraints it was decided that rather than constructing a new board, the inductance of the current limiting capacitor would be increased. This would limit the current being drawn into the circuit. This however limits the current in the work coil which resulted in the annealing time being longer than the original design parametres. The cartridge took 50s to go from 25°C to 400°C. An annealing time of 50s is too slow due to the high thermal conductivity of brass. This results in the wall of the cartridge becoming too soft which can become dangerous if reused. In order to confirm that the hardware design was corrected the annealing time was recalculated using the limited current value.

The difference in inductance between the current limiting indicator and the work coil meant that there was an impedance difference between the two elements. This impedance difference acted similarly to a voltage divider which is yet another reason to reduce the inductance of the current limiting circuit.

Figures 21a and 21b show the high and low side voltage output of the MOSFETs operating at a 150KHz. As can be seen in the images there is a sufficient amount of dead time to account for both the turn on and the turn off times of each MOSFET. There is also minimal ringing on MOSFETs due to the, use of snubber capacitors between the drain and gate of the MOSFETs. The diodes D2 and D3 as seen in appendix C.1 were removed as the reverse

(a) High Side Rising



(b) High Side Falling

Figure 21: Dead Time between the MOSFETs at 150Khz

current flowing out of the MOSFET damaged the IR2184 drivers. There was also a sufficient amount of dead time without the diodes being used.

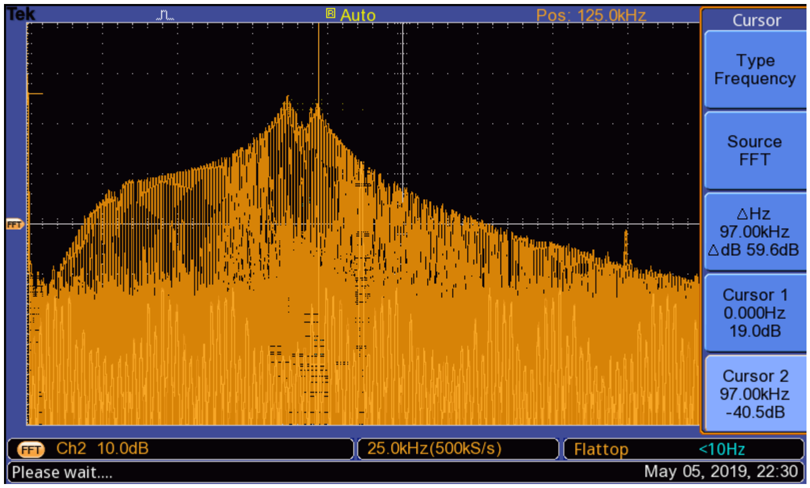


Figure 22: Resonant Frequency of the Tank Circuit

Figure 22 shows the FFT response of the tank circuit. The peak of the Bode plot is at 97KHz which is slightly lower than the calculated value. The deviation is most likely caused by the slight variance that each capacitor has. Although the value is lower than expected it is still within a good operating range. The decay in the Bode plot is also similar and matches the simulations performed as seen in Figure 16.

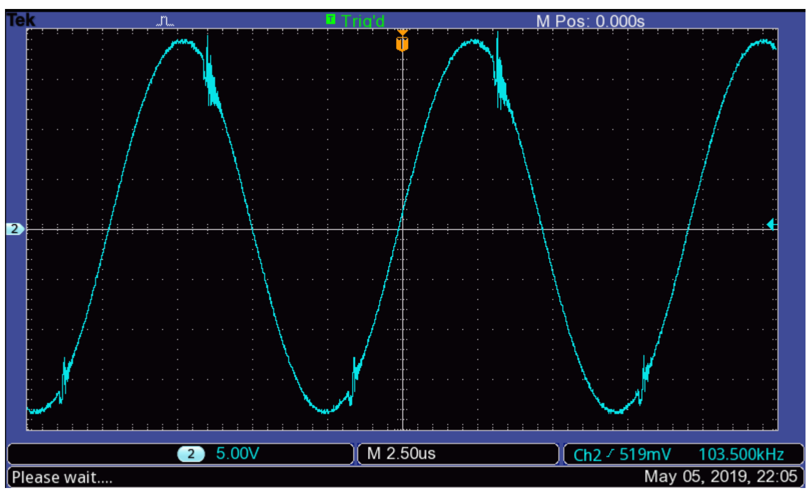


Figure 23: Output Voltage of Tank Circuit

The output over the work coil can be seen in Figure 23. The output behaves in the expected manner and the wave form closely resembles that of the simulation as seen in Figure 17a. There are oscillations on the sinusoidal output. These oscillations begin on the falling edge of the high side MOSFET and only occur during the dead time between the high and low side MOSFETs. The circuit is not being driven at resonant at this instant as can be seen by the oscillations being slightly offset. It should also be noted, as in the simulations, that the output voltage over the work coil grows significantly as it approaches resonant frequency.

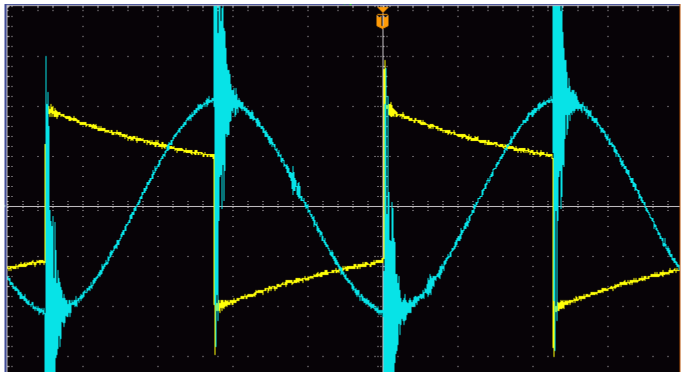


Figure 24: Operating Close to the maximum power point

Figure 24 indicates the tank circuit being driven at its resonant frequency. The DC input voltage was scaled down when this measurement was taken in order to show the relationship between the high side MOSFET and the resonant frequency of the tank circuit. It"s noted that the oscillations on the sinusoidal wave are at their peak when the voltage is also operating at its peak. These oscillations during the dead time indicate the importance of choosing MOSFETs of a higher operating voltage than the DC input voltage of the circuit.

Figure 25: Inductive Load measured across the current limiting inductor

Figure 25 shows the voltage measured across the current limiting indicator. The rising slope and the positive half cycle and the falling slope on the negative half cycle are indicators that the load is operating in the inductive region, as the current limiting indicator is absorbing energy when the high side MOSFET is on and then releasing it when it switches.

Figure 26 shows the output of the full-bridge rectifier. The circuit was only tested at 50V due to the voltage probes becoming to hot. There is a small ripple voltage that can be seen in the wave. This ripple will increase as the voltage increases. However due to the nature of the, circuit the ripple will have minimal effect on its ability to operate.

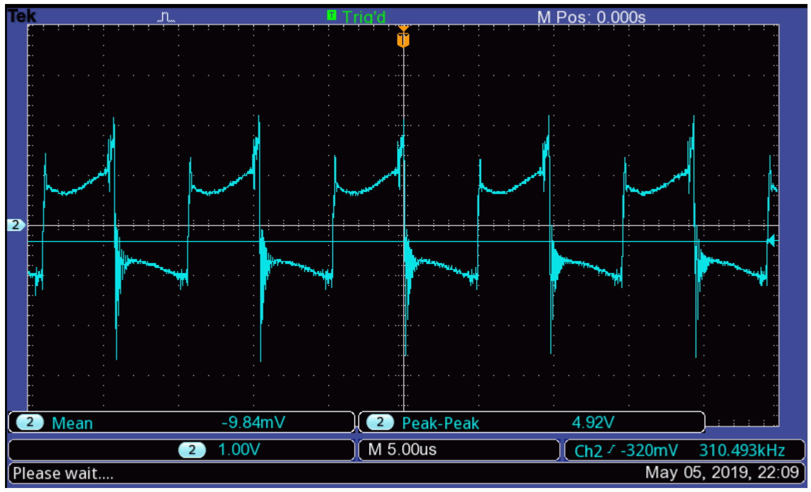
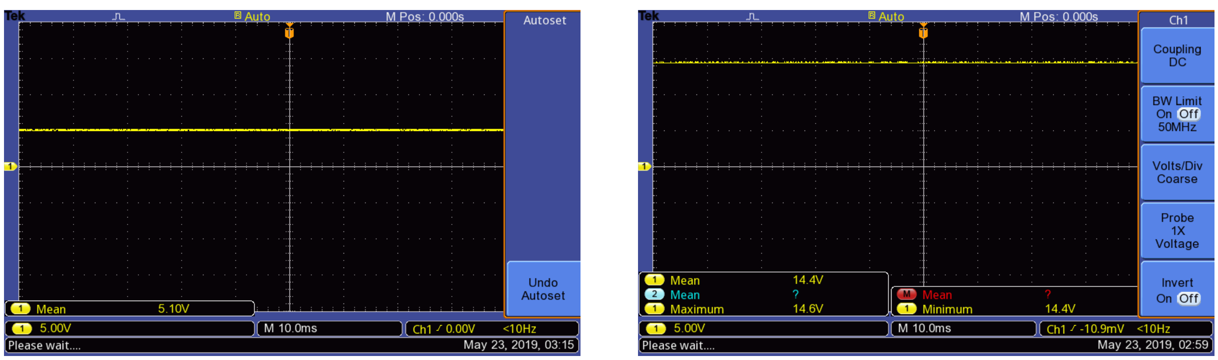


Figure 26: Output of Full-Bridge Rectifier

In Figures 27a and 27b the show the output of the zener diode voltage regulators. The outputs are not exactly as expected and fall at 5.4V and 14.4V respectively.



(a) 15V output

(b) 5V

Figure 27: Zener Diode Voltage Regulators

One element that was not considered during the design of the circuit was power loss due to thermal convection of the cartridge. As the cartridge increases in temperature it conducts heat to the air surrounding it which causes the air to heat up. The change in heat lowers its density causing it to rise, which in turn causes new colder air to replace it. This is an exponential process as can be seen in Figure 28. The loss of energy due to convection can be calculated using equation 29.

$$q = \varepsilon\sigma({T_{\mathrm{h}}}^4 - {T_{\mathrm{c}}}^4)A_{\mathrm{h}} \tag{29}$$

Where,
q is the thermal coefficient.
T_h is the temperature of the hot body.

T_c is the temperature of the surroundings.
A_h is the surface area of the object.
ε is the emissivity coefficient of the material.
σ is the Stephan-Boltzman constant which is 5.6703 10^{-8} $\frac{W}{m^2K^4}$

The total energy loss calculated while the bullet was at annealing temperature was 0.573W, but this value would be higher had it been summed throughout the annealing process. However, the energy loss at the maximum temperature is low enough for it to be neglected as time to anneal decreases.

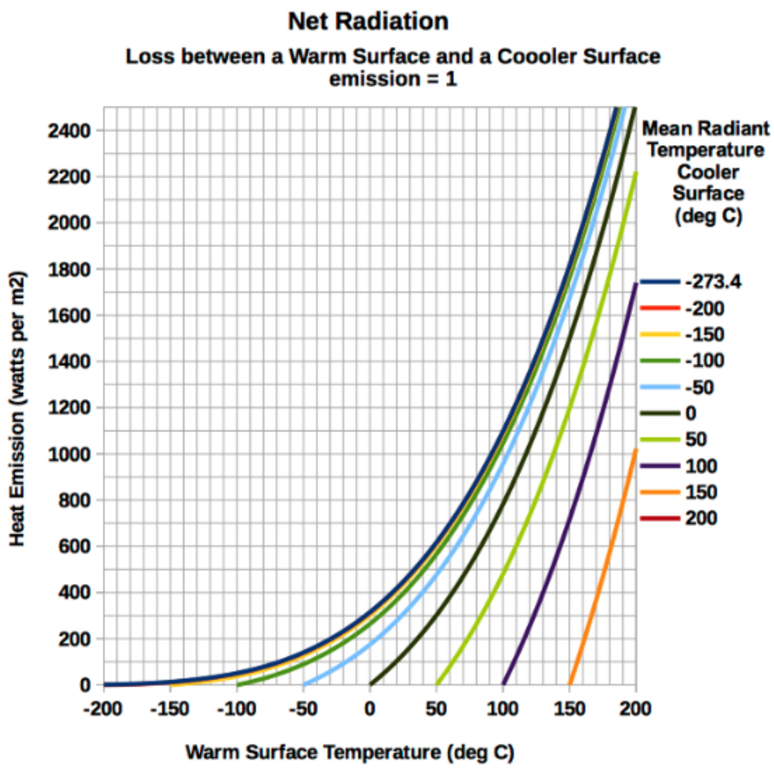


Figure 28: Heat Loss Due to Convection[32]

The power in the work coil was recalculated in order to calculate the energy needed to anneal the coil within 10s. The impedance of the coil was used to calculate the current going through it with V_{rms} = 26V the current through the coil is I_{rms} = 28.5A

This results in an annealing time of 50 seconds which is different to that of the theoretical calculations. This is a result of the coupling between the neck of the cartridge and the coil being very different from the theoretical value. The theoretical calculations were don't consider other factors. Testing suggests that decreasing the value of the current limiting inductor by a factor of 5 will increase the power and allow for a faster annealing time.

7 Conclusions

The document provides fundamental insights into the annealing process and how to build a circuit capable of annealing brass cartridges. Not all the goals stated in the above project statement were met, however the project highlights changes and improvements that would allow for the completion of the project had it not been for time constraints.

The fundamental goal of annealing a cartridge using induction. The annealing target of 10s was not. The results indicate that it can be met with minor alterations to the design, either by thickening the tracks or by using forced cooling. This would keep the tracks cool during the annealing process allowing the current limiting inductors value to be decreased. This would also allow more current in the work coil and in turn increase the speed at which the cartridge reached annealing temperature.

The current sensor and control of the circuit worked as expected, however it is stated in the recommendations that there may have been a better way to achieve the same result

The circuit wasn't operated using the power from a plug socket, however it operated well under full load conditions using a 300V DC generator. This suggests that operation from a plug socket should yield the same results. It should also be noted that at 300V the circuit only drew 1.4A which is well below the current that can be supplied by an AC wall socket, suggestings that if the current limiting inductor had to be reduced in size the circuit would be able to anneal the cartridge in the allotted time. It should also be noted that although the rectifier and the annealing circuit shorted during further testing, both circuits worked although they were not integrated.

8 Recommendations

The annealing target of 10s was not met by this project but the results indicate that it can be met with the current design. A better equation needs to be used to relate magnetic field to power transfer as it does not account for the fact that the cartridge of the bullet is hollow.

Although the current sensing worked as expected, the use of a negative feedback loop with a phase comparator with a 90° phase shift would have possibly been a better solution as it would have resulted in a faster change. A different controller should also be used to provide smaller increments and decrements on the PWM wave.

The tracks had the current capability for short periods, however with repeated use they got hot. Wider tracks are required to dissipate heat for prolonged use. Better thermal calculations on all components should also be considered in the design phase. Even though they operated within their rated temperature, it is easier to test and change the circuit and components if they are below 50°.

Buy a range of feritte cores so that a magnetic concentrator can be built and tested as this should help improve the speed and efficiency of the circuit.

Given more time, there are different iterations of the same circuit that could have been built and tested. For instance a full-bridge driver could have been used over a half-bridge driver. This could have been advantageous as a low side current sensors could have been placed on the side MOSFETs connection to ground.

Rather than removing the diode that sits across the gate resistor a better design would have been a higher ohm gate resistor and the discharge diode in series with a low ohm resistor. This would have given the IR2184 protection as well decreasing the turn off time for the gate.

The coil reached a temperature of 100 C° while heating the cartridge, while this did not cause any problems it is not ideal. This can be solved by using a hollow copper tubing in conjunction with a water pump to help regulate the temperature of the coil to an acceptable levels.

Forced cooling using fans could also be used on the circuit to help dissipate the heat generated in the circuit and is possibly another solution to prevent the tracks becoming too hot. Rather than making use of wider tracks, forced cooling would keep the tracks from overheating when the circuit is operating for extended periods of time.

Appendices

A Project Planning

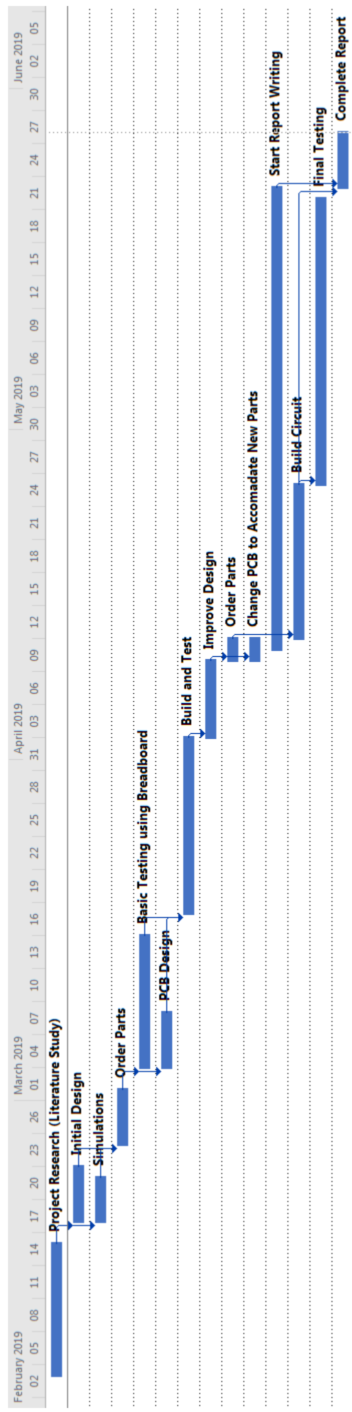


Figure A.1: Project Plan

B ECSA Outcomes Compliance

Problem solving: Identify, formulate, analyse and solve complex engineering problems creatively and innovatively	**4.2.1 , 4.3.1** (4.2.1) Analyzing the effects of inductive loading. Fixing the ringing on the capacitors due to parasitics. Prevent the MOSFET gate from floating by using a pull-down resistor. (4.3.1) Inductor to limit the current.
Application of scientific and engineering knowledge: Apply knowledge of mathematics, natural sciences, engineering fundamentals and an engineering speciality to solve complex engineering problems.	**5 , 4.3.1.2 , 4.2.1 , 4.1** (5) I used my knowledge of coding to create a control system for the circuit and generate a PWM signal. (4.3.1.2) I used my knowledge of resonant circuits to show the importance of operating at the correct frequency. (4.2.1) I used my knowledge to pick MOSFETs suitable for my application. (4.1) The effect the skin effect has.
Engineering Design: Perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.	**4.2.1.1 , 4.2 , 4.3 , 4.2.2** (4.2.1.1) Used my knowledge of thermal dissipation to design heat sinks. (4.1) The design of the work coil. (4.3) Design of the tank circuit. (4.2.2) Design of the full-bridge rectifier.
Investigations, experiments and data analysis: Demonstrate competence to design and conduct investigations and experiments.	**Chapter 6** Demonstrates an analyses of the circuit and the tests that were conducted. It assesses how well the circuit performed and discusses technical issues with possible solutions
Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.	**4.3** (4.3 , C) The above chapters show the ability to use spice simulations. C shows the ability to use design tools such as KiCad. The testing shows the ability to solve problems using engineering tools such as multimetres and oscilloscopes.
Professional and technical communication: Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.	The report aims to demonstrate a high level of understanding and convey the information in a clear and concise manner that can be followed by and engineering professional.

Individual work: Demonstrate competence to work effectively as an individual.	The project was researched, designed built and tested by myself. My supervisor provided helpful advice but never gave me the exact solution to the problem
Independent Learning Ability: Demonstrate competence to engage in independent learning through well-developed learning skills	All the work was completed independently by applying knowledge gathered from a variety of resources. My supervisor provided helpful advice and guidance that allowed to take the correct path to solve my problems.

C PCB layout

C.1 Circuit

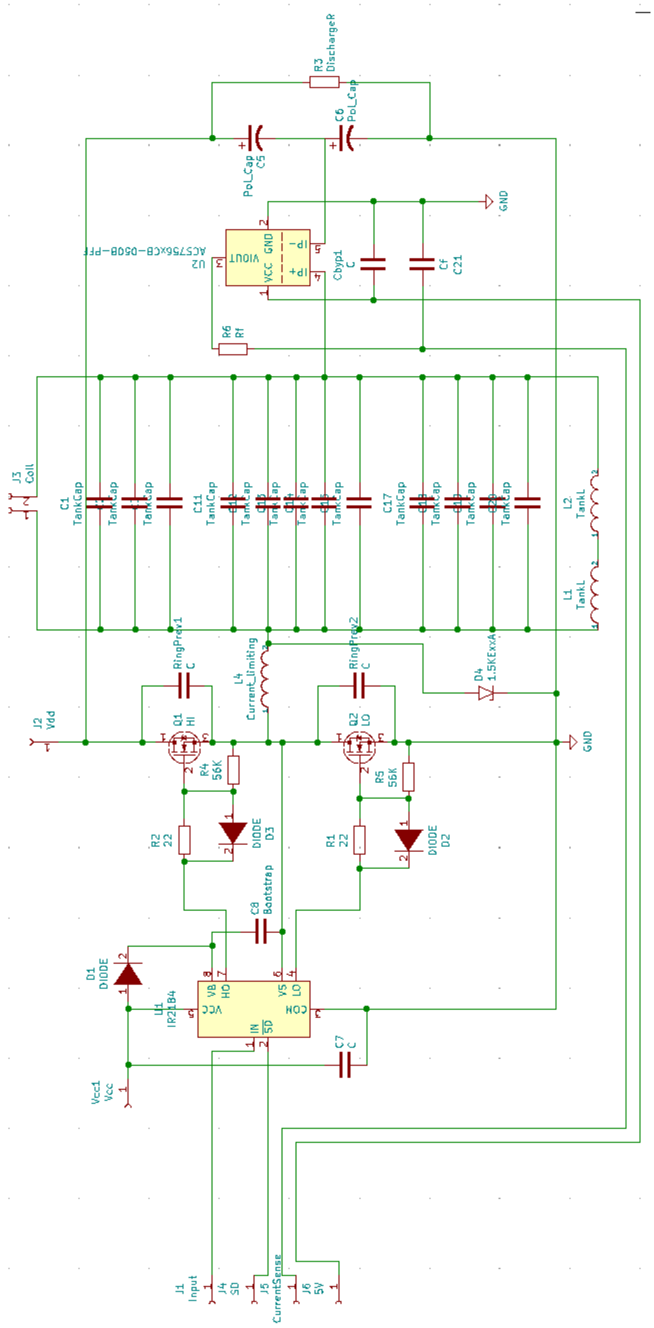


Figure C.2: Schematic

C.2 Top Copper Layer

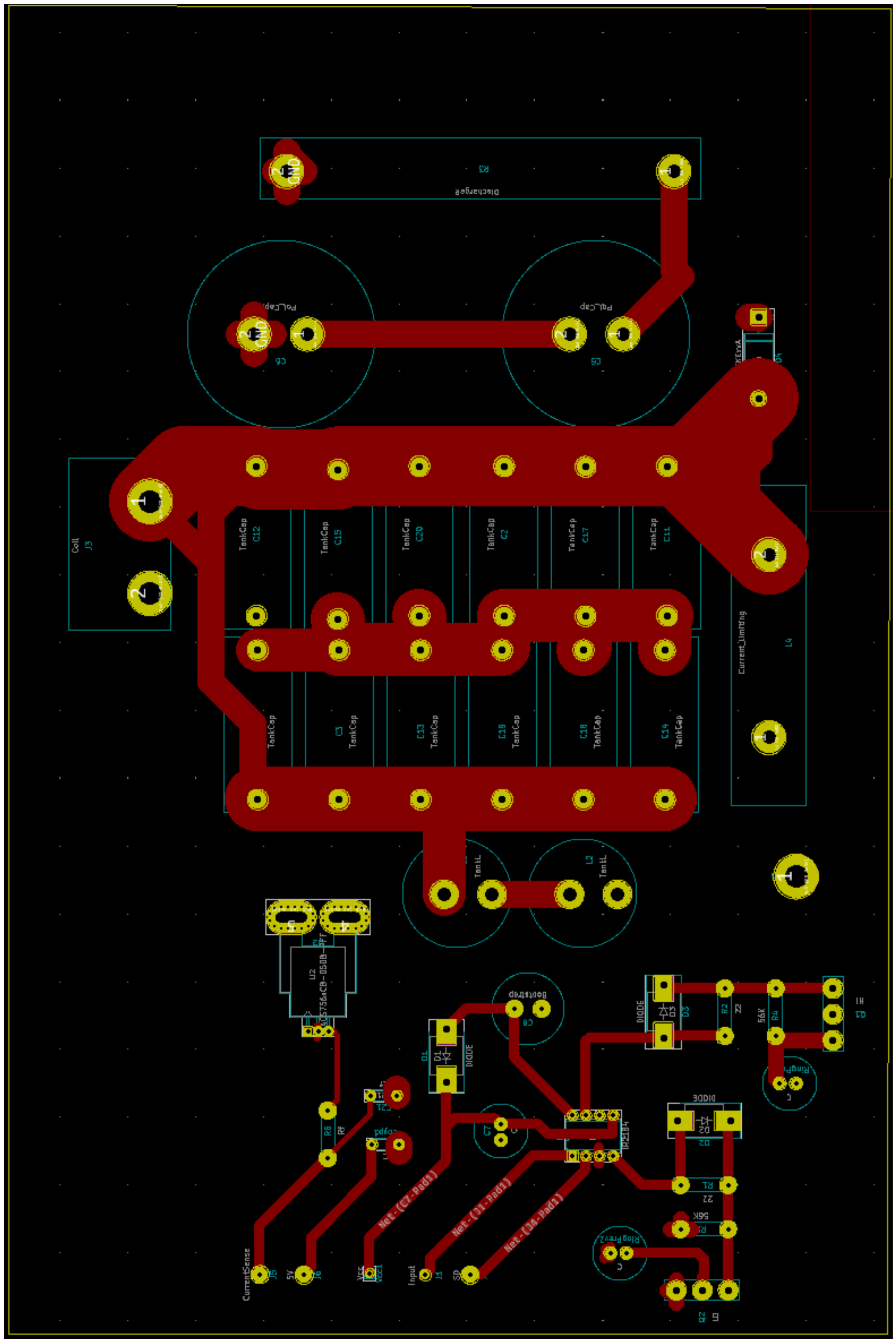


Figure C.3: The top tracks on the main PCB (Re-designed with thicker tracks)

C.3 Bottom Copper Layer

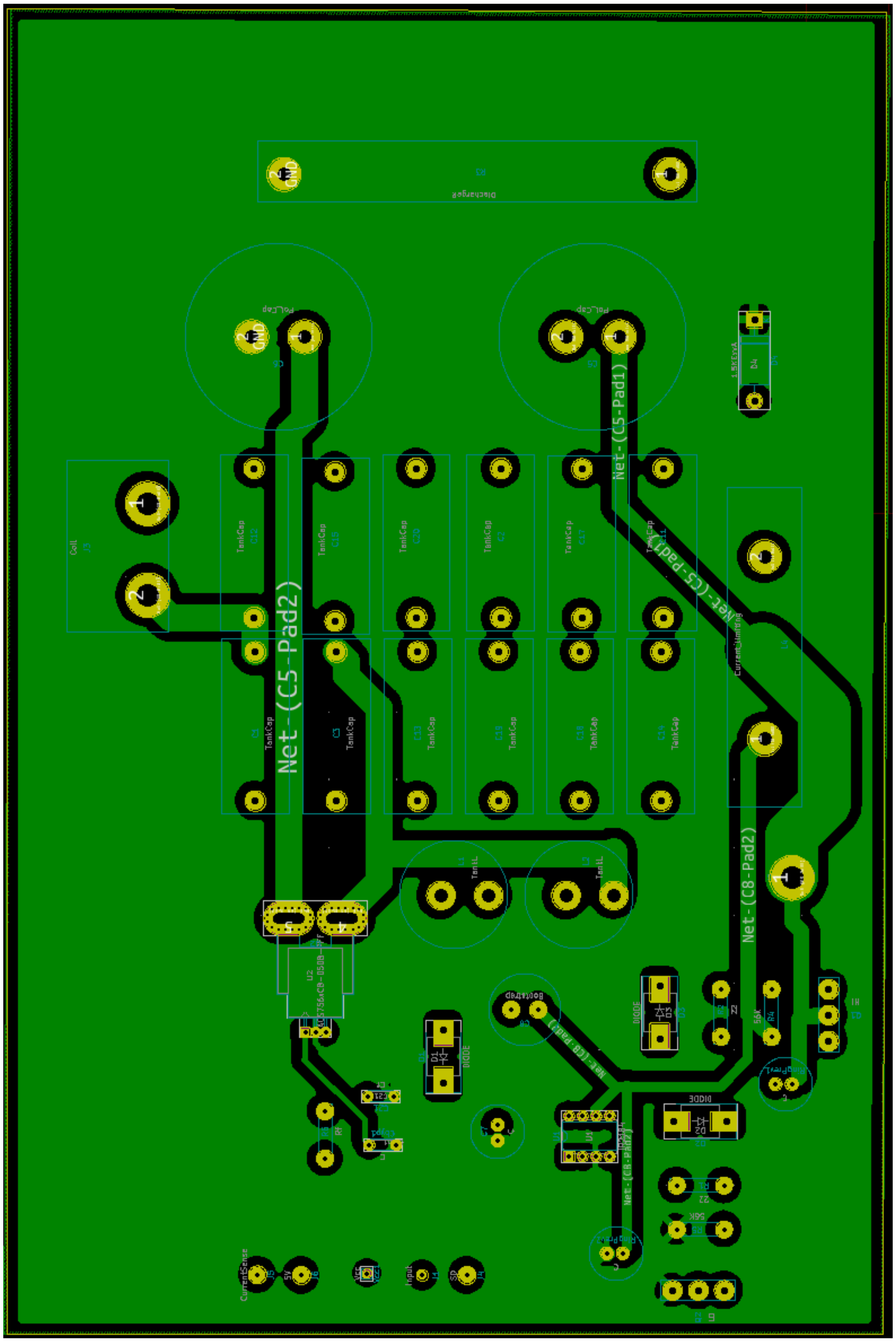


Figure C.4: The Bottom Tracks on the Main PCB

C.4 Full Bridge Rectifier PCB

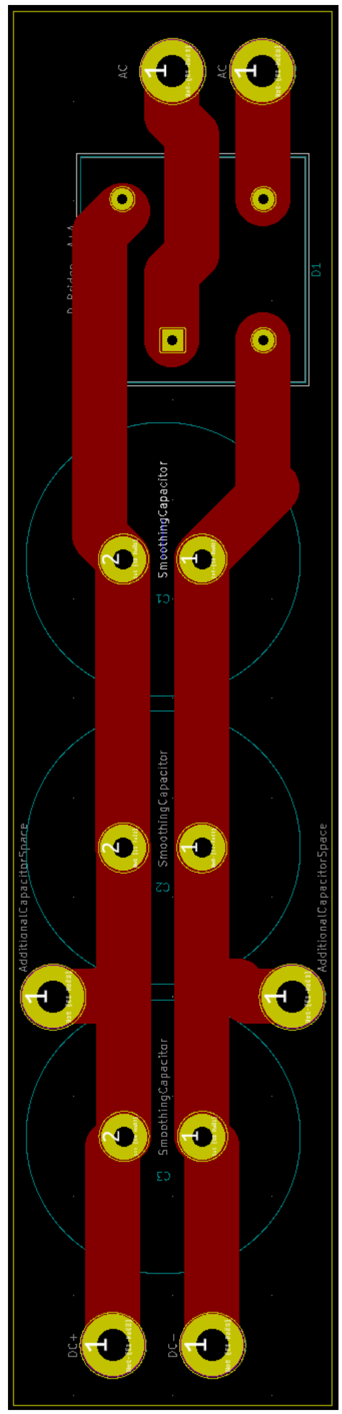


Figure C.5: Full Bridge Rectifier PCB

D Code

D.1 Control Flow

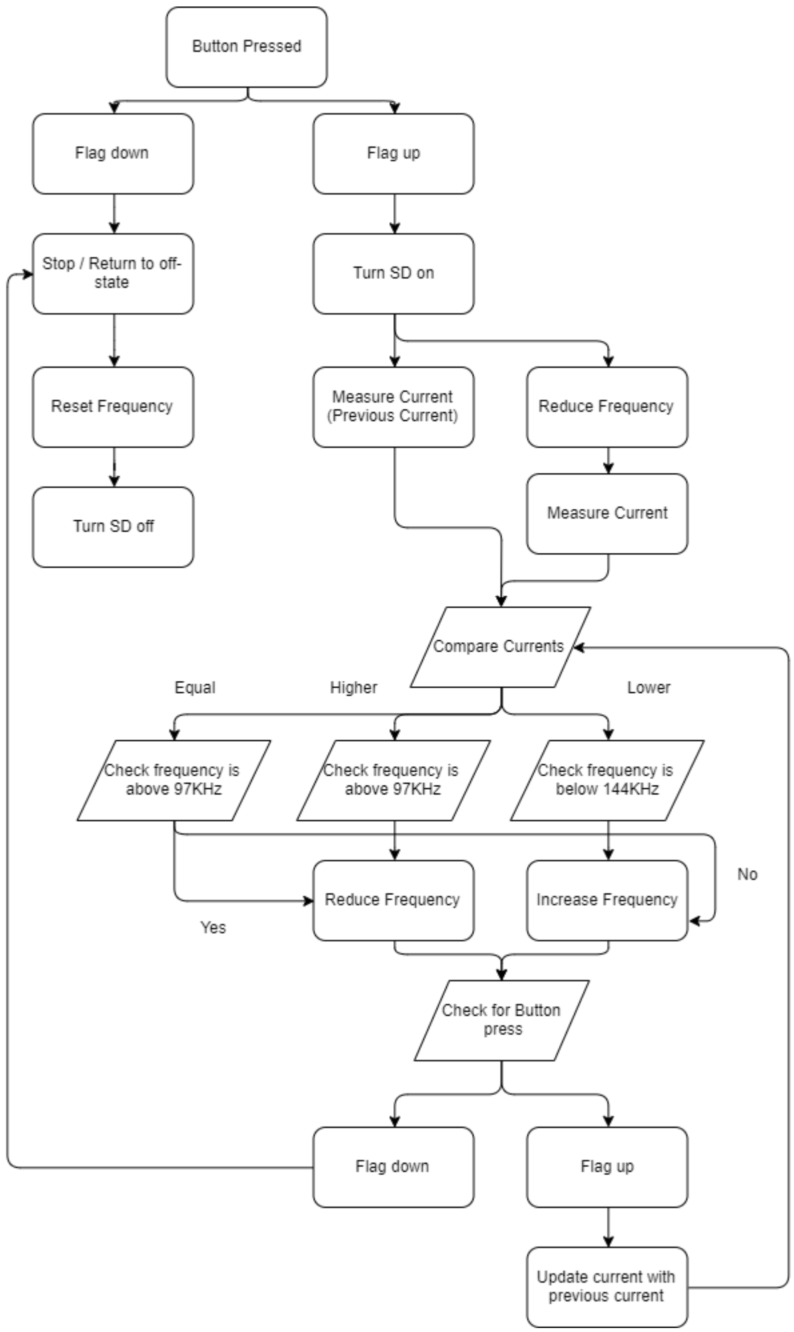


Figure D.6: Program Flow

D.2 Code

Listing 1: C code

```c
#include "main.h"


ADC_HandleTypeDef hadc1;

TIM_HandleTypeDef htim1;
TIM_HandleTypeDef htim2;

UART_HandleTypeDef huart2;

/* USER CODE BEGIN PV */
volatile uint8_t adcFlag, userFlag, firstClickFlag;
float adcCurrent, inVoltage , adcPrevCurrent, freqRC;
/* USER CODE END PV */

/* Private function prototypes -----------------------------------------------
void SystemClock_Config(void);
static void MX_GPIO_Init(void);
static void MX_TIM1_Init(void);
static void MX_USART2_UART_Init(void);
static void MX_ADC1_Init(void);
static void MX_TIM2_Init(void);

int main(void)
{

        HAL_Init();

        /* USER CODE BEGIN Init */
        firstClickFlag = 0;
        adcFlag = 0;
        adcCurrent = 0;
        userFlag = 0;
        adcPrevCurrent = 0;
        freqRC = 500;
        /* USER CODE END Init */

        /* Configure the system clock */
        SystemClock_Config();
```

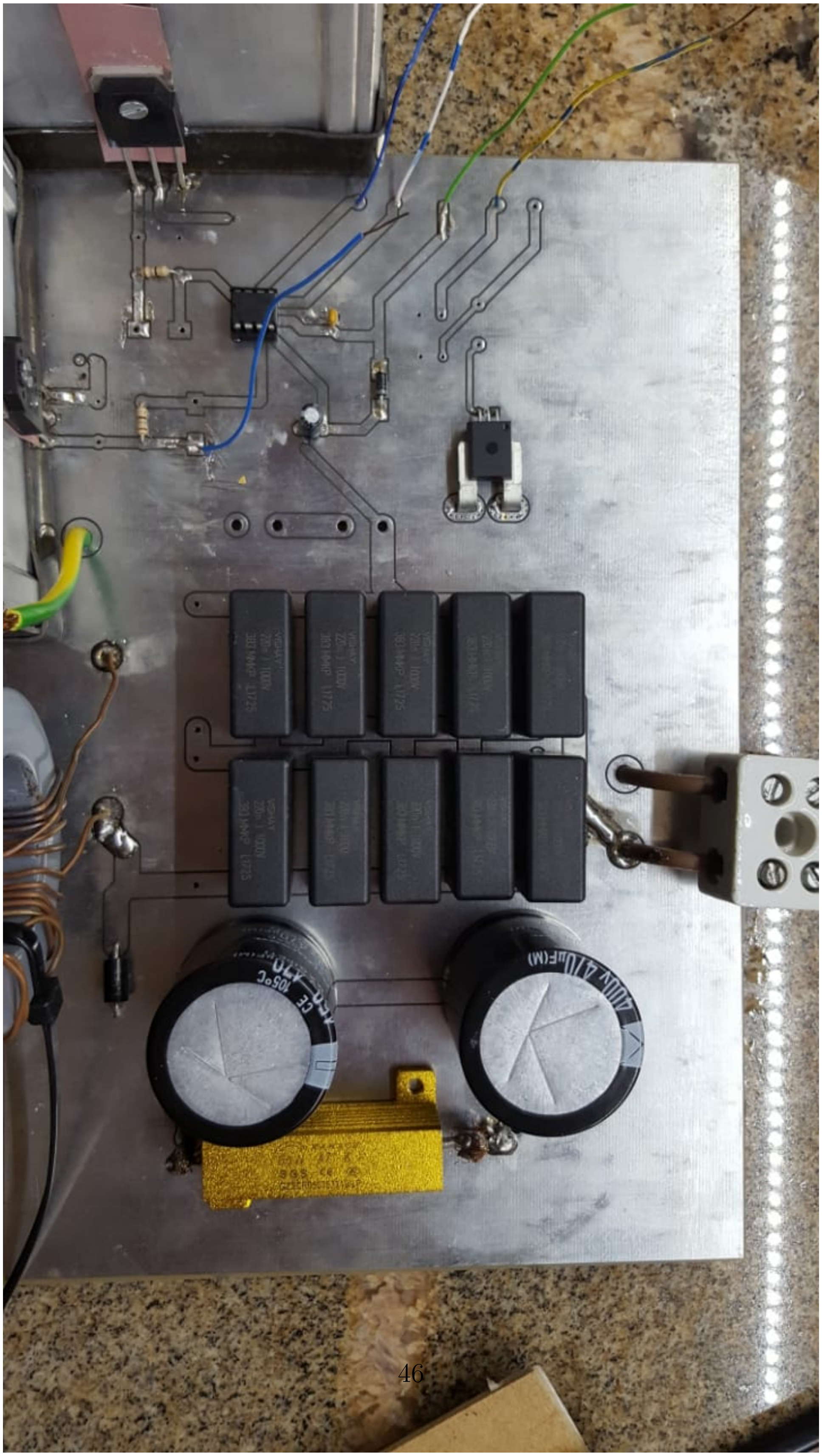
```
MX_GPIO_Init();
MX_TIM1_Init();
MX_USART2_UART_Init();
MX_ADC1_Init();
MX_TIM2_Init();
/* USER CODE BEGIN 2 */
HAL_TIM_PWM_Start(&htim1, TIM_CHANNEL_1);
htim1.Instance->ARR = 500;
htim1.Instance->CCR1 = 250;
htim2.Instance->ARR = 500;
__HAL_TIM_ENABLE(&htim2);
__HAL_TIM_ENABLE_IT(&htim2, TIM_IT_UPDATE);

HAL_ADC_Start(&hadc1);
HAL_ADC_PollForConversion(&hadc1 , 100);


while (1)
{
	//button press
	if(!HAL_GPIO_ReadPin(GPIOC, GPIO_PIN_13))
	{
		if(firstClickFlag)
		{
			userFlag = !userFlag;
		}
		else
		{
			userFlag = 1;
			firstClickFlag = 1;
		}

		if(userFlag)
		{
			HAL_GPIO_WritePin(GPIOA, GPIO_PIN_5, 1);
			HAL_Delay(200);
		}
		else
		{
			HAL_GPIO_WritePin(GPIOA, GPIO_PIN_5, 0);
			HAL_Delay(200);
			freqRC = 500;
			htim1.Instance->ARR = 500;
			htim1.Instance->CCR1 = 250;
		}
```

```
        }
    if(userFlag)
    {
        if(adcFlag)
        {
            adcFlag = 0;

            //sample adc values
            inVoltage = HAL_ADC_GetValue(&hadc1);
            //prime for next sample
            HAL_ADC_Start(&hadc1); //starts it
            HAL_ADC_PollForConversion(&hadc1 , freqRC);
            //read values?
            //proccing
            inVoltage = (inVoltage)/4095 * 3.3 + 0.2;
            //some voltage between 0 and 3.3
            adcCurrent = 0.5 * inVoltage + 2.5;
            //gives current proportional to this voltage

        if(adcCurrent < (adcPrevCurrent*0.95)
        || adcCurrent > (adcPrevCurrent*1.05) )
        {
            if(freqRC < 738)
            {
                if(adcPrevCurrent < adcCurrent)
                {
                    freqRC = freqRC + 1;
                }
                else if(freqRC > 500)
                {
                    freqRC = freqRC - 1;
                }
            }
            htim1.Instance->ARR = freqRC;
            htim1.Instance->CCR1 = freqRC/2;
            adcPrevCurrent = adcCurrent;
        }
        else if(freqRC < 738)
        {
            freqRC = freqRC + 1;
        }
        //do stuff with this current but first calibrate

        }
```

```
        }
            /* USER CODE END WHILE */

            /* USER CODE BEGIN 3 */
        }
        /* USER CODE END 3 */
}
```

E Built Circuit

E.1 Annealing Circuit



E.2 Full-Bridge Rectifier and Zener Diode Voltage Regulator

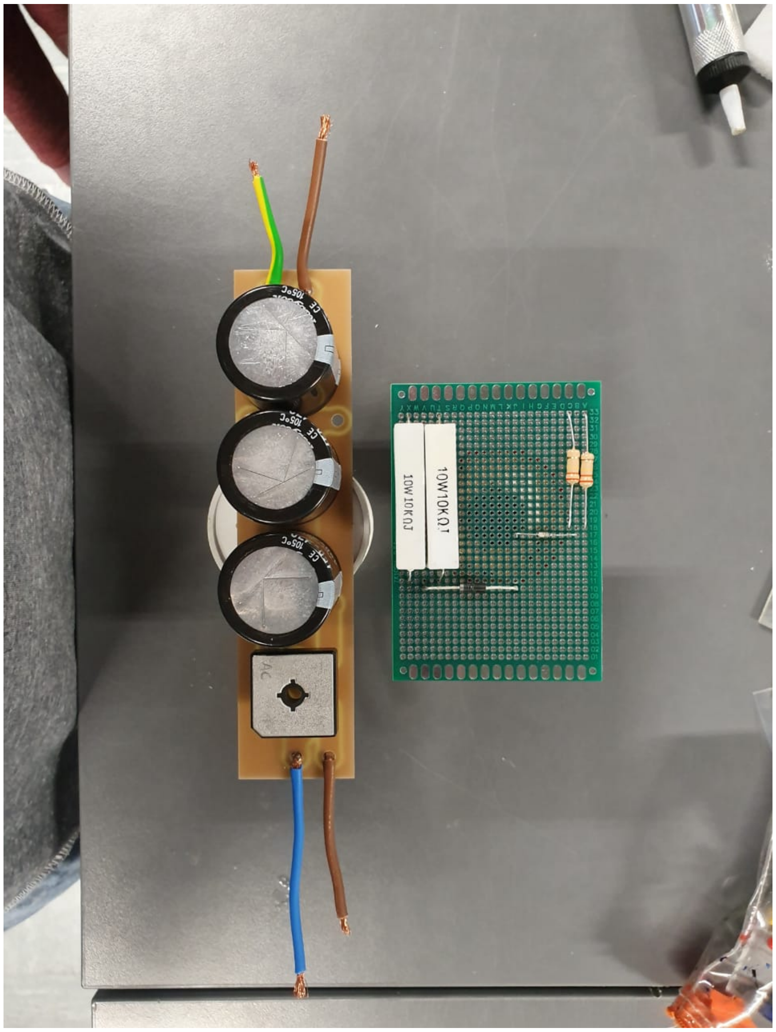


Figure E.8: Full-Bridge Rectifier and Zener Diode Voltage Regulator

E.3 Heated cartridge

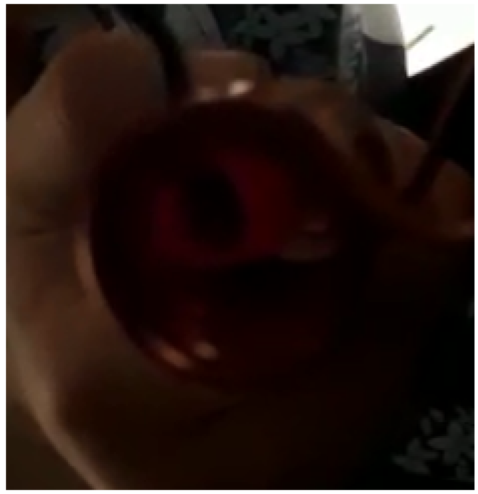


Figure E.9: Heated Cartridge

The red glow can be seen around the neck of the cartridge. The cartridge is being held off centre in order for it to make contact with the temperature sensor.

Figure E.10: Temperature of cartridge after 50 seconds in the work coil

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