School of Electrical Engineering

The University of Western Australia

# Capacitive Spot Welder for Renewable Energy Vehicle Project

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# Nomenclature

| | |
|---|---|
| IGBT | Isolated-Gate Bipolar Transistor |
| LED | Light Emitting Diode |
| LiFePO4 | Lithium Iron Phosphate Battery |
| MIC4452 | Non-Inverting Mosfet Driver |
| MOT | Microwave Oven Transformer |
| NE555P | 555 Timer |
| REV | Renewable Energy Vehicle |

# Chapter 1

## Introduction

## 1.1 Background

The Renewable Energy Vehicle (REV) Project at the University of Western Australia is committed to the construction of zero emission electric vehicles.  Engineering students across multiple disciplines research ways to advance electric vehicles to become a viable alternative in the future.  The latest project is to design and build an electric Formula SAE car for an international competition hosted in Melbourne. It will be judged on vehicle design and performance.  The electric vehicle must rely on a large battery bank that can not only provide large amounts of instantaneous power for acceleration, but also have a high capacity for endurance. The bank is comprised of 3.2V 3.2 Ah LiFePO4 battery cells that measure 26.2 mm D x 65.2 mm H.  These individual cells are divided into two battery boxes positioned along the sides of the vehicle to add structural support. Each of these boxes consists of 16 cells connected in series by 40 parallel to produce 25.6V.  In total, the Formula SAE car relies upon 640 batteries cells that need to be firmly linked together due to the large amount of mechanical stress placed on the frame

## 1.2 Project Objective

To ensure that the electrical connection remains intact the batteries need to be spot welded together.  Spot welding is a type of resistance welding that uses a large amount of current to melt two metal surfaces together (Miller Electric 2010).  Spot welding creates a connection that is much stronger than soldering.  The REV project has a spot welder; however, the electrodes are opposing each other.  To weld to the top of the batteries a spot welder had to be built with electrodes that are parallel to each other.

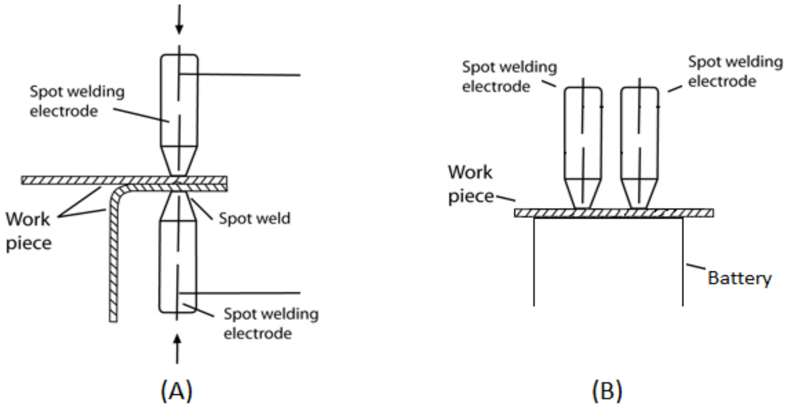


Figure 1: (A) Current REV Spot Welder (Courtesy: Wilkinson)
(B) Design Needed to Weld to the Surface of a Battery

There are two main types of spot welders: transformer and capacitive. Both designs involve a low resistance system to generate a high current. The highest resistance in the main circuit has to be through the welding surface so that the majority of the power is dissipated on the surface. The power is dissipated as heat which causes the metals to melt together. Another key component to a spot welder is a control system. Spot welding needs the timing to be controlled so that the spot is not under or over welded. If the spot is under welded, the bond will be weak and can easily break apart. On the other hand, if the spot is over welded the entire spot will melt, causing a hole which could compromise the battery (Miller Electric 2010).

## 1.2.1 Aims

The aims of this project were:

1. To compare transformer spot welder designs to capacitive spot welder designs.
2. To design and implement an optimal spot welder with parallel electrodes.
3. To design and implement a control system to regulate welding time.
4. To test the system and refine timing and voltage.
5. To weld the 640 batteries for the SAE vehicle onto laser cut sheet metal templates.

# Chapter 2

## Evaluation

## 2.1 Transformer Spot Welder

Transformer spot welders tend to be the most common homemade spot welder because they are relatively simple and inexpensive (Wilkinson 2011).

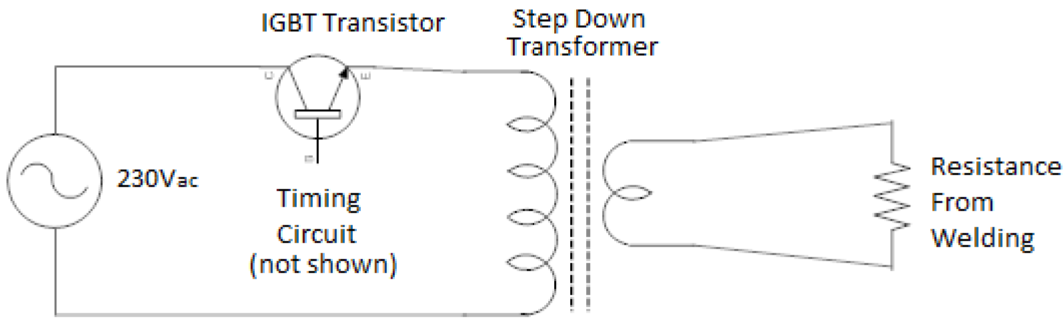


Figure 2: Transformer Spot Welder

The Transformer spot welder is convenient because it can be powered directly by a wall socket. A spot welder requires at least 100A (depending on the material and thickness) and typical wall sockets are restricted by a circuit breaker to a maximum 30A. This design, however, uses a step down transformer to allow a large current through the welding surface without drawing too much current from the source.

$$I_w = \frac{N_s}{N_w} I_s$$

Equation 1: Current in an Ideal Transformer

Equation 1 shows that the current through the weld, $I_W$, equals the current drawn from the source, $I_S$, multiplied by the ratio of the number of turns in the transformer on the source side, $N_S$, to the number of turns on the weld side, $N_W$. Typical handmade transformer spot welders use a microwave oven transformer because the primary coil generally has 230 turns and the secondary coil is replaced by three turns (Homemade 2008). This allows for the spot welder to use 100A while only drawing 1.3A from the source. The exact current, however, depends on the resistance of the welding material. The IGBT is used as a switch to control the duration of the weld.

## 2.2 Capacitive Spot Welder

The Capacitive spot welder uses a DC power supply to charge up a bank of capacitors that can produce a large current (Pemberton 2009). Battery tab welding typically requires 15Vdc to achieve an optimal current across the welding area.

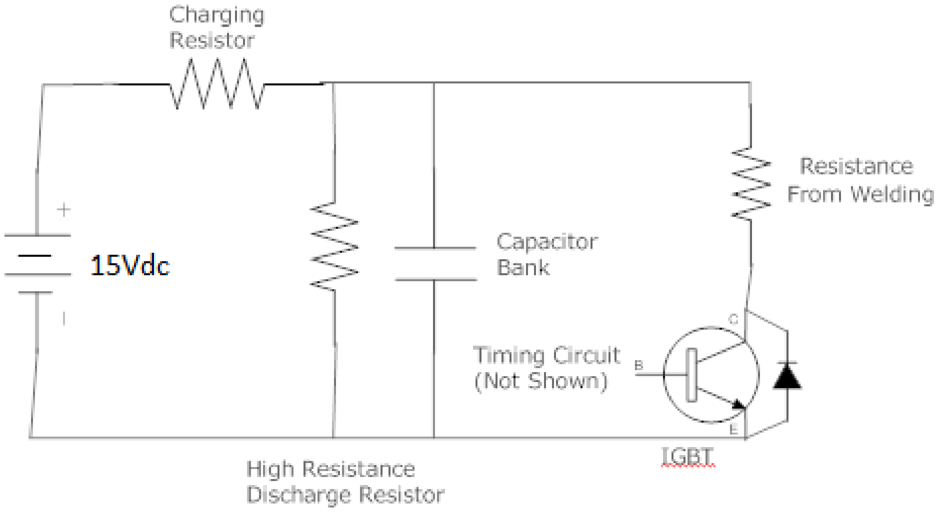


Figure 3: Capacitive Spot Welder

The power supply cannot be used solely to supply this voltage because it is current limiting. The DC power supplies in the REV lab are limited to output 330mA. Instead capacitors are used to store a large amount of charge and can output a large current when discharged. One of the difficulties with this design, however, is that the current changes with time as the capacitor discharges.

$$I = \frac{V_0}{R} e^{-t/RC}$$

Equation 2: Capacitor Discharge Current

The current through the weld, I, is proportional to the supply voltage, $V_0$, over the resistance of the weld, R, but it decreases in time, t, according to the time constant, the weld resistance times capacitance of the bank, C. For a stable current the spot welder will need a large RC. Since the resistance must remain low to produce a large current the design needs to have a large capacitance. If the RC is high enough the change in current over the duration of the weld is negligible. The weld time is controlled by an IGBT placed in series with the welding electrodes. A crucial safety feature of this design is the high resistance discharge resistor. Without this component the capacitor bank would remain charged almost indefinitely when turned off. A small leakage current could take several days to discharge a large capacitor bank and someone could be accidentally shocked. At a maximum of 15V, a shock would not be severe, but the risk should still be avoided. The discharge resistance is high to minimize its effect on the charging and discharging of the bank for welding.

## 2.3 Comparison

Both the transformer and capacitive spot welder designs have the potential to produce a large current and could be used to weld the batteries together. Transformer spot welders are more widely used because they produce a stable current and tend to be inexpensive to build. The main component is a MOT, which can be cheaply acquired from a junkyard (Watkins 2009). The capacitor spot welder however requires both a DC power supply and a large capacitance. A large capacitance can be reached using ultracapacitors. Ultracapacitors are fairly inexpensive and have a high capacitance; the only drawback is that they must be operated at low voltage. Other capacitors of the same capacitance are extremely expensive. If used in series these capacitors can reach 15volts, while achieving a high enough capacitance to output a semi-stable current when used to weld. Additionally the REV lab has spare ultracapacitors and power supplies available. This means a capacitive spot welder could be built at no additional cost to the REV project. The main concern against building a transformer spot welder is the input of 230V. This can produce a hazardous shock making this welder much more dangerous than a capacitive. Due to safety concerns and the availability of certain components, a capacitive spot welder was built for the Formula SAE project.

# Chapter 3

## Design

### 3.1 Initial Design

The initial design for the capacitive spot welder was designed using the bare minimum components necessary to construct a welder. Also at this point a timing circuit had not yet been devised.

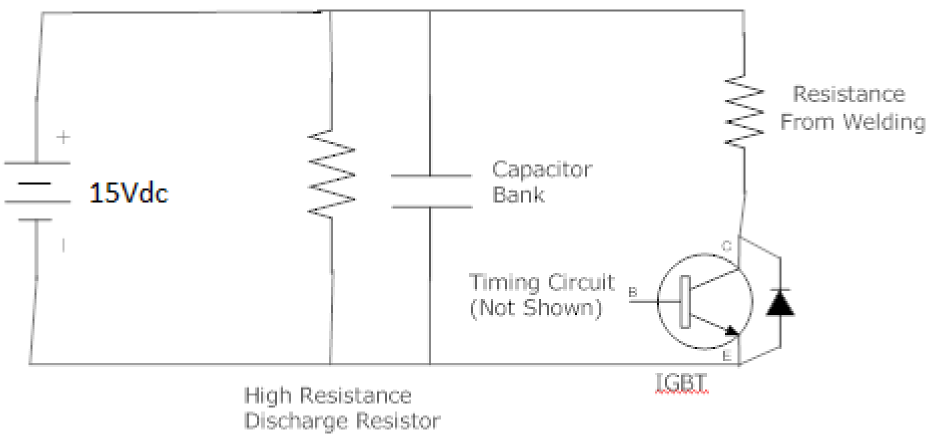


Figure 4: Initial Spot Welder Design

The design consists of three major components: the capacitor bank, a discharge circuit, and a timing circuit. A timing circuit runs an IGBT for a short pulse. The timing circuit should output a single pulse for approximately 10ms for a solid weld and to avoid overheating the electrodes (Miller Electric 2010). The IGBT draws power for welding from the capacitor bank across the electrodes. An IGBT is necessary because it has to be exposed to the welding current and can handle up to 600A. The discharge circuit is only necessary for when the welder is no longer in use so that the capacitor bank can be discharged completely. This initial design for the discharge circuit is extremely inefficient because by having a large resistance for minimal effect to the welding process it takes a large amount of time to discharge. To power down the circuit quickly the resistance would have to be low, but this would draw too much power from the capacitor when welding. This initial design needs to be changed to include a timing circuit and an efficient discharge system.

## 3.2 Capacitor Bank

In order for a large capacitance, BCAP0350 ultracapacitors were used to construct the bank.


Figure 5: Ultracapacitors (Courtesy: Maxwell Technologies)

Each of these has a capacitance of 350 Farads but must remain under 2.5 Vdc. In order to reach the 15Vdc necessary for spot welding, 6 capacitors had to be connected together in series.

$$C' = \frac{C}{n} \qquad\qquad C = \frac{Q}{V}$$

(A) (B)

Equation 3: (A) Equivalent Capacitance of Capacitors in Series
(B) Capacitance in Terms of Charge Over Voltage

Using equation 3A, identical capacitors in series have an equivalent capacitance, C', equal to their individual capacitance, C, over the number in series, n. The 6 ultracapacitors in series have a total capacitance of 58.33 Farads. Equation 3B relates this capacitance, C, to the charge stored in the bank, Q, over the voltage, V. For the capacitor bank to be completely charged it requires 874.95 Coulombs of charge. Since the REV lab power supplies limit output current the supply can be directly applied across the capacitor bank without a charging resistor. The current when charging remains a constant 330mA.

$$t = \frac{Q}{I_c}$$

Equation 4: Charge Time due to Constant Current

The time to fully charge the capacitor bank can be found using equation 4. The time, t, in seconds is equal to the charge, Q, over the constant current, Ic. Due to the large capacitance, it takes approximately 44.2 minutes to charge. This large capacitance is necessary, though, to keep the discharge current close to constant. Using equation 4, the charge necessary to maintain a constant 100A for 10ms is 1 Coulomb. Subtracting this from the fully charged bank leaves 873.95 Coulombs in the capacitors. The resulting voltage from equation 3B is 14.98V. This approximation shows that the voltage drop across the capacitors is negligible when used for welding and can be treated as constant. A constant voltage means that the capacitance is great enough the current can be treated as constant. The power supply takes 3 seconds to recharge the 1 Coulomb used in welding.

## 3.3 Discharge Circuit

A circuit had to be designed that could discharge the capacitor bank when not in operation. The initial design was simply a high resistance connected across the terminals of the bank. This however is extremely inefficient because it draws power from the bank during operation and slows charging. A high resistance is used to minimize these effects; however, this creates extended discharge times. To solve these problems a circuit was designed with a low resistance that is connected across the terminals of the capacitors by a switch. The switch is open during operation to not effect charging and welding discharge. When not in use the switch is closed allowing for faster discharge times. A LED in parallel with another resistor was added in series to display whether the capacitor bank is charged.

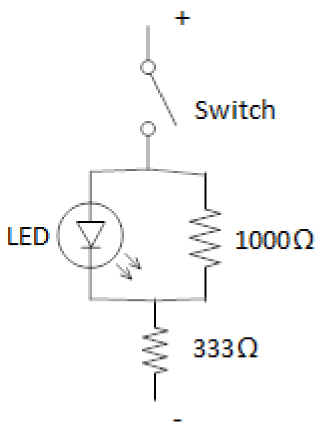


Figure 6: Final Discharge Circuit

As long as the voltage across the capacitor ban k is greater than 2.2V, the LED will be lit when discharging. The current through the circuit is approximately given Equation 5.

$$I = \frac{V_i - V_{Don}}{333} \; for\; Vi > 2.2V \quad I = \frac{V_i}{1333} \; for\; V_i < 2.2V$$

Equation 5: Current through Discharge Circuit

Initially the diode can be treated as a short across the 1000Ω resistor that requires 2.2 V, $V_{Don}$, to produce light. The current, I, is the capacitor bank voltage, $V_i$, minus the $V_{Don}$ over the 333Ω resistor as long as $V_i$ is greater than $V_{Don}$. Once the voltage fall below the 2.2V needed to produce light current no longer flows through the LED, instead it flows through the 1000Ω resistor in series with the 333Ω resistor. Combining equation 2 with equation 5 gives the current through the circuit over time as the capacitors discharge.

$$I = \frac{V_0 e^{-t/RC} - V_{Don}}{333} \; for \; V_0 e^{-t/RC} > 2.2V \qquad I = \frac{V_0 e^{-t/RC}}{1333} \; for \; V_0 e^{-t/RC} < 2.2V$$

Equation 6: Current Discharging from Capacitor Bank Over Time

The time constant for the first part of discharge is 333Ω times 58.33 Farads. The second part has a time constant of 1333Ω times 58.33 Farads. Using the first time constant and 15V across the capacitor bank, it takes approximately 10.35 hours before the voltage falls below 2.2V. This reduces the voltage to a harmless level and the capacitors can be shorted to remove the remaining voltage. Otherwise the capacitors will continue to dissipate power but at an extremely slow rate.

## 3.4 Monostable Pulse Circuit

One of the most crucial components of the spot welder is the timing circuit. It is the control system that starts and regulates the welding time. If not controlled properly the weld could be weak or the integrity of the battery compromised. Spot welding battery tabs is typically done in 10ms pulses (Pemberton 2009). A microprocessor was originally considered for producing the pulse; however, a 555 timer circuit was used instead. A 555 timer circuit was chosen because a monostable pulse circuit could easily be created and adjusted without programming. The initial design for the monostable pulse circuit was adapted from Hewes and can be seen in figure 7 (2011).

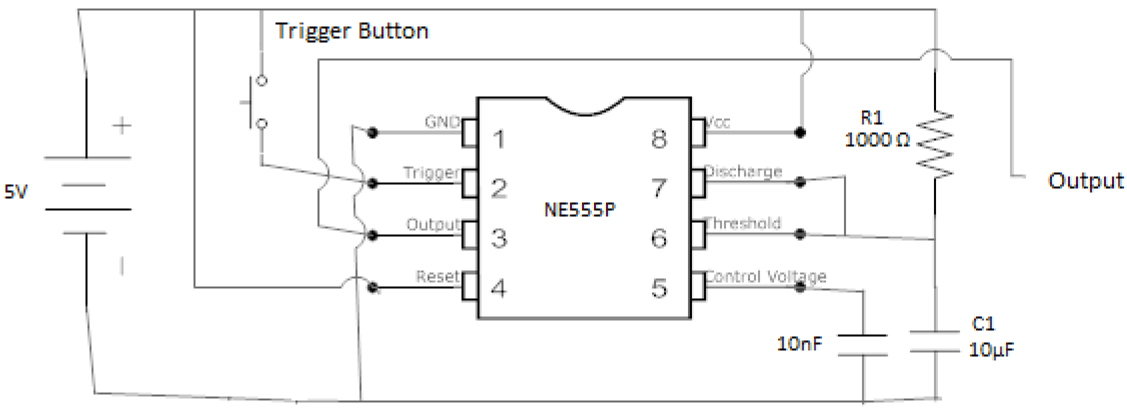


Figure 7: Original Design for Monostable Pulse Circuit

When the NE555P timer is triggered the discharge pin connected to C1 is cutoff from ground causing C1 to charge. While C1 is charging, the output pin is driven to Vcc. C1 continues to charge until the voltage seen from the threshold pin is (2/3) Vcc. At this point the capacitor is discharged and Output pin is driven to back to GND. The reset pin must remain high or else there will not be a pulse. The duration of the pulse is determined by the values for R1 and C1 as seen in equation 7.

$$T = R_1 C_1 ln(3)$$

Equation 7: Monostable Pulse Duration (Courtesy: Hewes 2011)

The duration of the pulse, T, is equal to the time constant of R1 and C1 times the natural log of 3. The timing circuit for the REV spot welder uses 1000Ω for R1 and10µF for C1for a pulse duration of approximately 10.99ms. There is a problem in the original design in figure 7. The trigger in the circuit above remains low until the button is pushed driving it to high. The NE555P, however, is triggered by a low voltage. The only time that the circuit above is not trigger is when the button is pressed. To fix this the components surrounding the trigger were set to remain high unless a button was pressed as seen in figure 8.

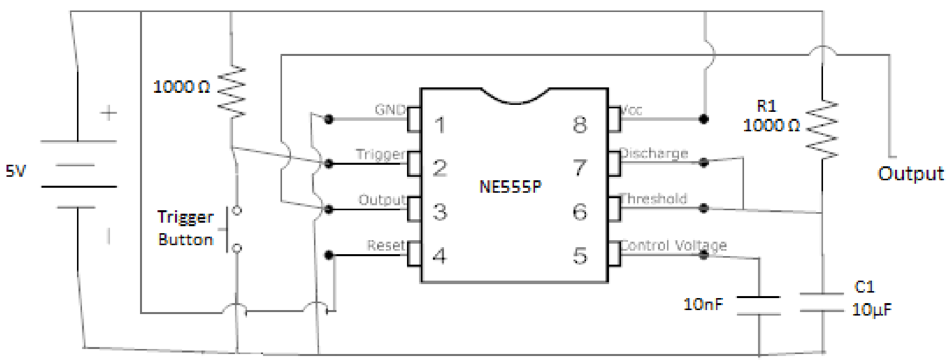


Figure 8: Second Design for Monostable Pulse Circuit

This design ensures that the circuit is only triggered when the button is pressed.  When attached to an oscilloscope, however, the pulses output by the circuit were high for various lengths of time and all longer that 11ms.  This was due to the fact that the button was triggering the circuit for longer than the intended pulse width.  Additionally the button would occasionally bounce causing multiple pulses per push.  To fix both of these problems the button was replaced with a switch in series with a parallel 0.1μF capacitor and 1000Ω resistor before connecting to ground.

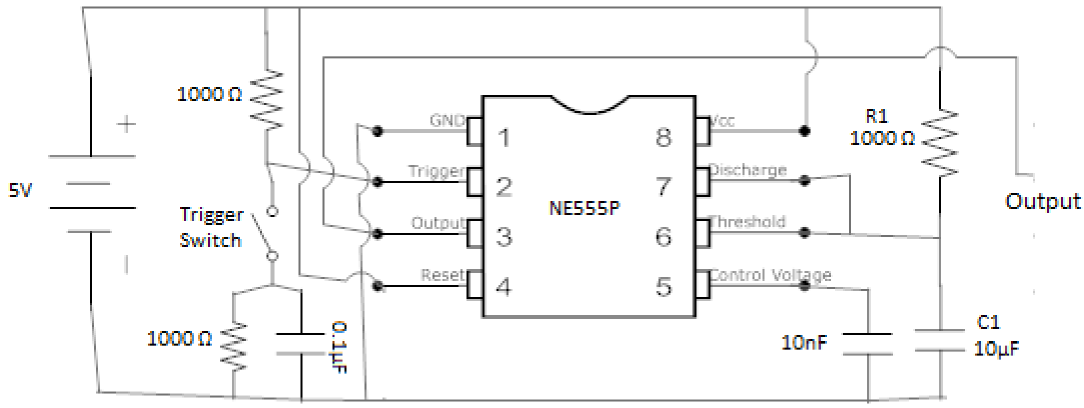


Figure 9: Final Design for Monostable Pulse Circuit

When the switch is thrown the capacitor is initial uncharged and acts as a short allowing for the trigger to be driven to GND.  As soon as it is charged to (1/3)Vcc the circuit is not longer triggered and the switch has to be reset before it can be fired again.  Its small capacitance allows it to reach (1/3)Vcc long before the end of the pulse time.

$$V_t = \frac{V_{cc}}{2}(1 - e^{-20000t})$$

Equation 8: Voltage over Trigger Capacitor over Time

Equation 8 was solved using Laplace transforms for the voltage, $V_t$, over the 0.1μF capacitor when the switch is closed over time, t.  The capacitor takes 54.9μs before charge is above (1/3)Vcc which is far less than the pulse time.  Using equation 2, once switched off it takes 0.109 ms for the capacitor to discharge and ready to fire.  When connected to the oscilloscope it was observed that the circuit outputted a pulse for slightly less than 11ms.  The initial pulse should be close to 11ms because there are delays in other places in the spot welder causing the weld time to be close to 10ms.

# 3.5 MOSFET Driver

The MIC4452 MOSFET driver is used at the output of the timing circuit to increase voltage of the pulse to 12V. A higher voltage at the base of the IGBT increases the current flow through the welding site. Another advantage is that it can output up to 2A allowing for the IGBT's base capacitance to be charged faster. The IGBT has a base capacitance of 120nF that must be charge to allow current to flow. The MOSFET minimizes the delay in the IGBT switching on.

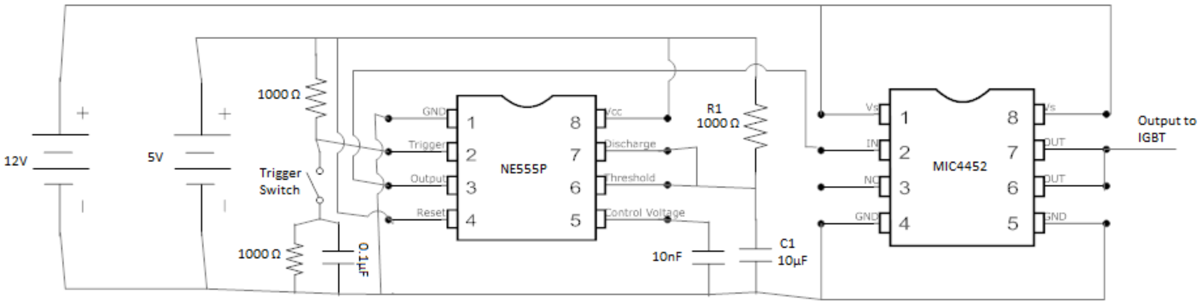


Figure 10: Timing Circuit with MOSFET Driver

The MIC4452 does have a delay when switching but it is extremely minute. By adding together the first delay time to the rise time and subtracting the second delay, given by the data sheet, the MOSFET shortens pulses by 5ns. This is negligible compared to an 11ms pulse.

# 3.6 Final Design

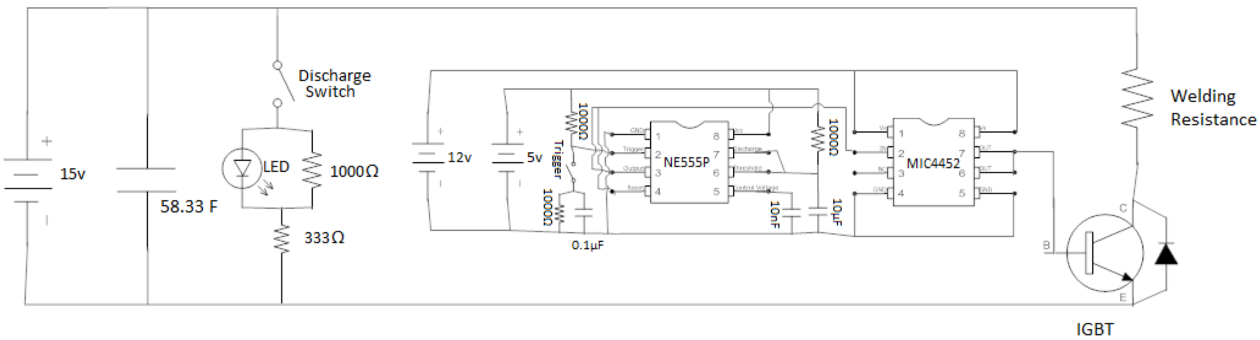


Figure 11: Final Design

The Final Design incorporates all of the separate components as one system. When initially turn on with capacitors at zero charge the spot welder will take approximately 44minutes to fully charge. Once charged the trigger switch can be thrown to send a 11ms pulse to the base of the IGBT.  This will drive a high current of around 100A through the welding surface and melt the metal underneath the electrodes.  The capacitors then require 3seconds to recover lost charge.  When finished using the discharge switch is closed and the voltage will reach a safe 2.2V after 10 hours.  This system is much more efficient than the initial design because the discharge time would have been much longer with a high resistance.

# Chapter 4

# Discussion

## 4.1 Initial Discussion

The capacitive spot welder was built to the specifications from the final design on a solderless breadboard. The control circuits were tested using a volt meter and oscilloscope and all values match the theoretical design predictions. Thick copper wire with a diameter of 6mm was used to connect the capacitor bank to the IGBT. The ends of this wire were then stripped and used as temporary welding probes. It is important to use thick wire to minimize resistance. The majority of the energy needs to be dissipated on the welding surface. Nickel is commonly used for spot welding because it has a higher resistivity compared to Copper so will absorb the majority of the energy (American Society 1979). The REV lab never ordered the nickel sheets to connect the batteries so the exact resistance could not be measured. Additionally without the exact resistance the spot welders timing and voltage cannot be calibrated to optimal performance. The capacitive spot welder however was tested on some small copper wires and strips. The copper strips were successfully welded together; however, the weld was not very strong. This was expected because the low resistance of copper makes it harder to weld. Every time the spot welder was tested on copper the voltage across the capacitors fell to 14.98V. This is the same value found in section 3.2 when the capacitors were discharged at a constant 100A. The capacitor spot welder is operationally, however, cannot be used or refined until tested on nickel strips.

## 4.2 Operation

1) Set the variable voltage on the power supply to 15 volts.
2) Connect the 15 volt supply across the capacitor bank.
    -Will take 44 minutes to fully charge.
3) Connect the 5 volt supply to the $V_1$ on the breadboard (Timing circuit)
4) Connect the 12 volt supply to $V_2$ on the breadboard (MOSFET Driver)

5) Connect the 5 volt and 12 volt ground to the common ground on the breadboard

6) Connect the positive end of the capacitive bank to $V_4$ and the negative to the common ground.

-Make sure that the discharge switch is turned off.

7) When capacitor bank is fully charged press electrode ends firmly against the welding surface and flip the firing switch.

8) After 10ms flip off firing switch and allow the bank to recharge.

9) When finish turn off power supply and switch the discharge switch.

-Will take 10 hours to fall below 2.2 Volts

* Gloves and goggles should be worn during operation to avoid burns and protect against flying sparks. Never hold close to electrode tip when welding.

## 4.3 Conclusion

The spot welder is operational and after being adjusted to the welding material will be able to firmly attach the 640 batteries to metal templates. The capacitor bank was successful able to produce a semi-stable current of 100A over the 10ms welding period. The testing of the system not only matched theoretical values but showed that it is capable of welding metal together. The spot welder can be either adjusted by changing the weld time or adding voltage. The timing can be adjusted by varying the $R_1$ resistor in the timer proportionally to the change in time. To add move power to the spot welder the voltage has to be increased. To increase the voltage more capacitors have to be added in series. This decreases the overall capacitance and causes the current to be less stable overtime. The setup could be greatly improved by designing a clamp to hold the welding electrodes together on top the battery and sheet metal. This would allow the spot welder to be operated from a safer distance when firing. Additionally the welds would be more uniform from having the electrodes at a constant distance apart.

# Chapter 5

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# Appendix A Photographs of Capacitive Spot Welder

Photo of Entire System:

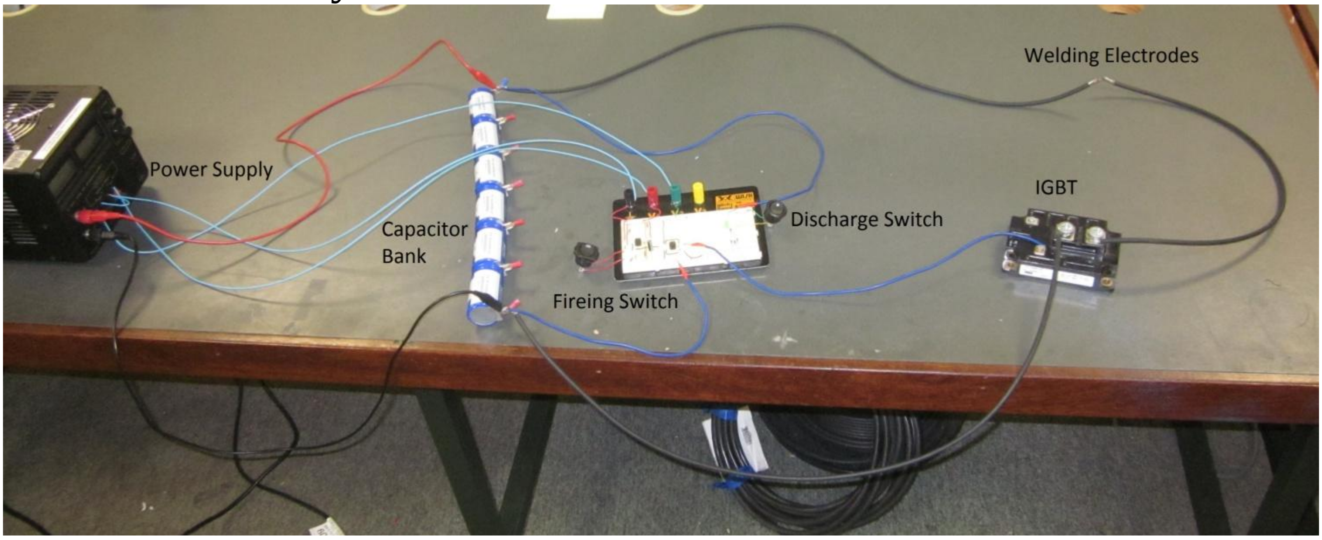


Photo of Timing Circuit with MOSFET Driver:

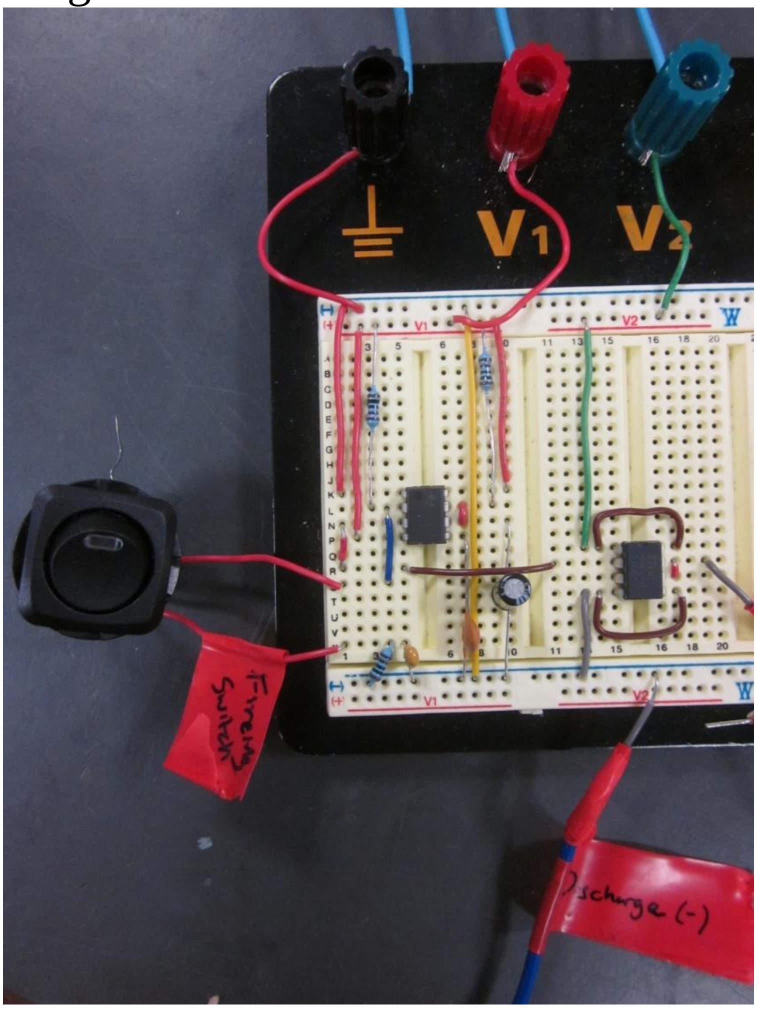

Photo of Discharge Circuit: