Special Problems for Undergraduates

CPE 400

Spring Quarter 2023

High Voltage Electronic Solenoid Controller for Combat Robotics

Author:

Pixie Macke

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Overview:

This project aimed to design a control system of a solenoid, similar to a brushless motor ESC, with the goal of using this circuit to power a flipper weapon on a 3-pound combat robot for competing in the beetleweight class of the National Havoc Robot League (NHRL). The circuit consists of an STM32 microcontroller, a flyback converter to charge a high voltage photoflash capacitor, a firing circuit, and a failsafe to discharge the capacitor in the event of a fault.

Design Considerations:

In the sport of combat robotics, the beetleweight class is a 3-pound weight class. The NHRL Bot Design Rules allow an additional 2 pounds for non-traditional locomotion i.e., locomotion without wheels, and an additional 1 pound for having multiple bots, for a possible total weight of 6 pounds. So, the controller must be able to power a solenoid with enough force for the flipper to be able to lift at least 6 pounds.

The NHRL Bot Design Rules also specify safety requirements that a robot must meet. It needs to pass a failsafe test such that the weapon comes to a stop within 60 seconds of radio signal loss. The robot must also have a physical power cutoff that can be deactivated within 15 seconds. Since the weapon's energy is stored in a capacitor instead of a traditional spinning disk, the failsafe has been designed to also meet the power cutoff requirements, discharging the capacitor under 15 seconds of a fault.

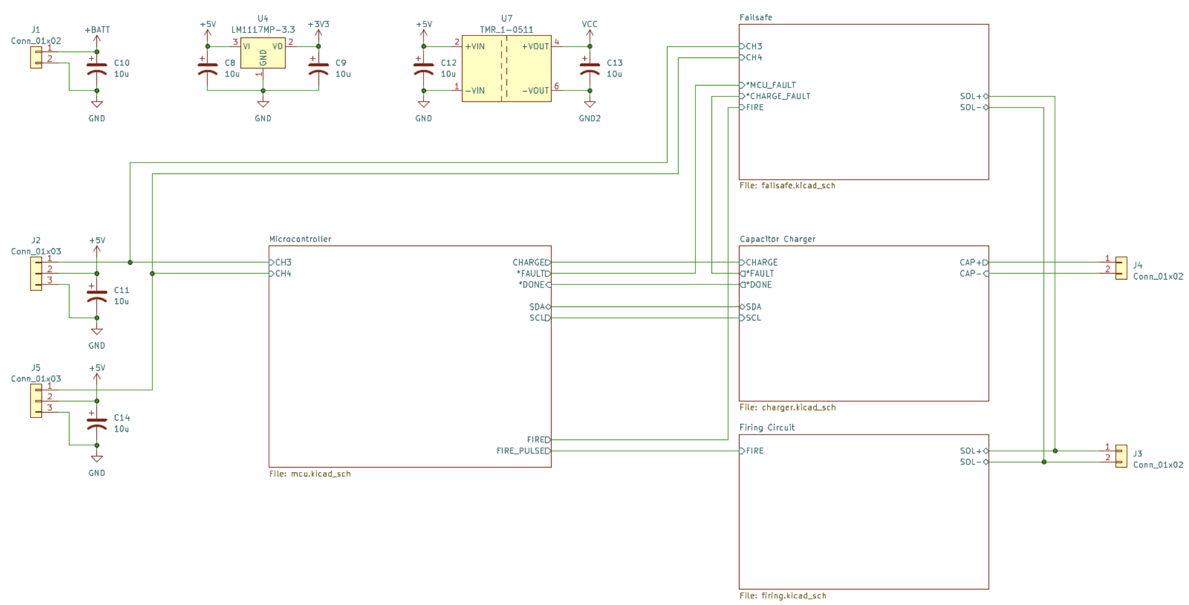

Figure 1. Controller Overview Schematic

Capacitor Charger:

The capacitor charging circuit is based on the LT3751 High Voltage Capacitor Charger Controller with Regulation. Charging current is set with the current sense resistor across CSP and CSN. The output voltage is set with the selection of R_{BG}. To allow the output voltage to be controlled by the weapon operator, this resistor is replaced with an AD5259 Digital Potentiometer. The LT3751 also features a fault indication pin that is output to the failsafe circuit.

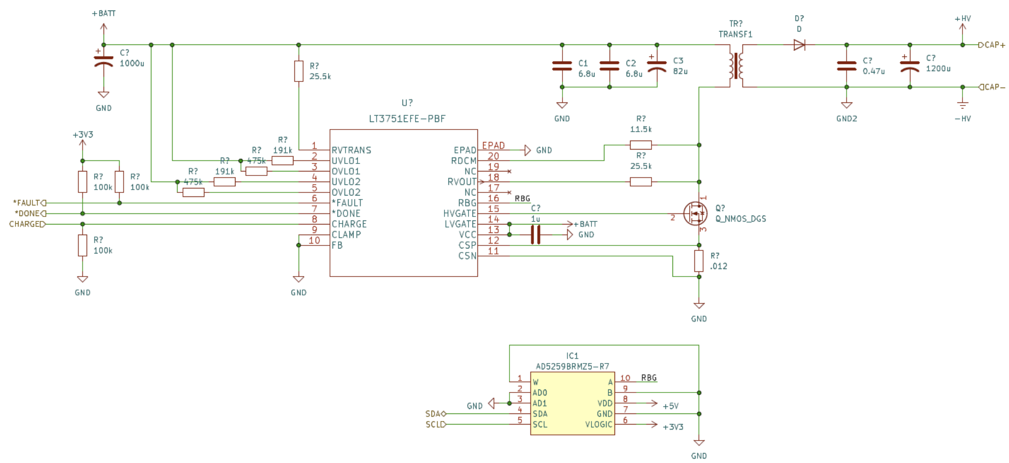

Figure 2. Capacitor Charger Schematic

The fault indication pin is triggered when an overvoltage or undervoltage occurs on either V_{CC} or V_{TRANS}. As these are both tied to the positive battery terminal, the required sense resistors will be the same for both rails, chosen by the following the equations:

$$V_{UVLO} = 1.225 + 50\mu A * R_{UVLO}$$

$$V_{OVLO} = 1.225 + 50\mu A * R_{OVLO}$$

The transformer is chosen from the recommended components in the LT3751 datasheet, focusing on the current limit and size to balance the charge time and weight of the transformer. The current limit is set by $106mV/R_{SENSE}$.

MANUFACTURER	PART NUMBER	SIZE L × W × H (mm)	MAXIMUM I_{PRI} (A)	L_{PRI} (µH)	TURNS RATIO (PRI:SEC)
Coilcraft	DA2033-AL	17.4 × 24.1 × 10.2	5	10	1:10
www.coilcraft.com	DA2034-AL	20.6 × 30 × 11.3	10	10	1:10
	GA3459-BL	32.65 × 26.75 × 14	20	5	1:10
	GA3460-BL	32.65 × 26.75 × 14	50	2.5	1:10
	HA4060-AL	34.29 × 26.75 × 14	2	300	1:3
	HA3994-AL	34.29 × 28.75 × 14	5	7.5	2:1:3:3*
Würth Elektronik/Midcom	750032051	28.7 × 22 × 11.4	5	10	1:10
www.we-online.com	750032052	28.7 × 22 × 11.4	10	10	1:10
	750310349	36.5 × 42 × 23	20	5	1:10
	750310355	36.5 × 42 × 23	50	2.5	1:10
Sumida	C8117	23 × 18.6 × 10.8	5	10	1:10
www.sumida.com	C8119	32.2 × 27 × 14	10	10	1:10
	PS07-299	32.5 × 26.5 × 13.5	20	5	1:10
	PS07-300	32.5 × 26.5 × 13.5	50	2.5	1:10
TDK	DCT15EFD-U44S003	22.5 × 16.5 × 8.5	5	10	1:10
www.tdk.com	DCT20EFD-U32S003	30 × 22 × 12	10	10	1:10
	DCT25EFD-U27S005	27.5 × 33 × 15.5	20	5	1:10

*Transformer has three secondaries where the ratio is designated as PRI:SEC1:SEC2:SEC3

Figure 3. LT3751 Datasheet Recommended Transformers

The output voltage that the capacitor is charged to, with the resistance across the digital potentiometer as RV_{OUT}, is set by the following equation:

$$V_{OUT} = 0.98 * N * \frac{RV_{OUT}}{R_{BG}} - V_{DIODE}$$

Firing Circuit:

The firing circuit is designed to quickly dump the energy stored into the capacitor into the solenoid in a safe and reliable way. Thyristors were chosen as the switching component because of their ability to shunt large amounts of power. Two were placed in series for redundancy, in order to prevent an accidental firing on a short circuit. A pulse transformer is used to trigger the SCRs so that they trigger simultaneously and so that the microcontroller stays isolated from the high voltage rail.

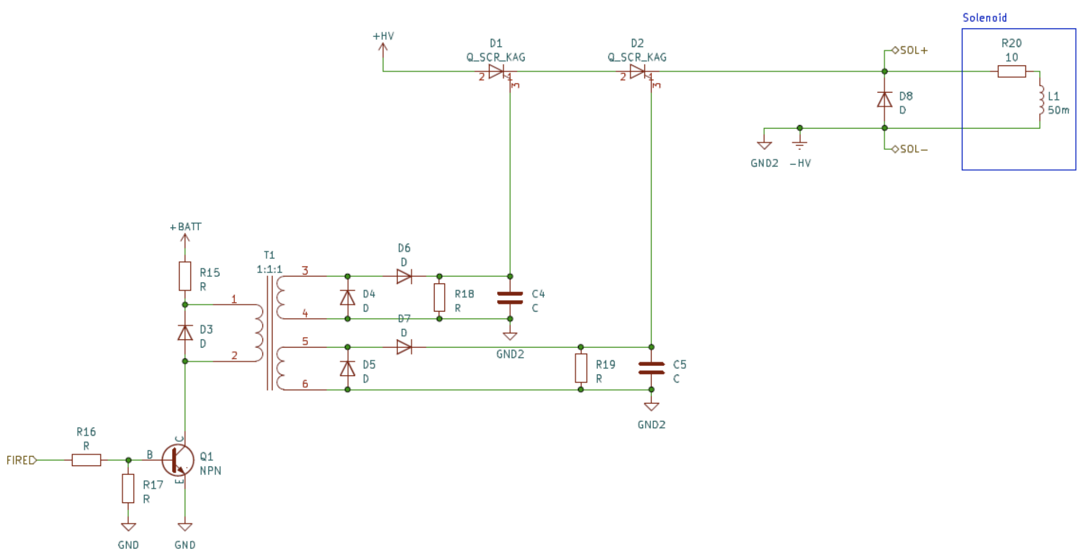

Figure 4. Firing Circuit Schematic

Failsafe:

The failsafe consists of a chain of transistors ANDed together, connected to each fault signal in the circuit, such that if a single signal goes low, the failsafe will trigger. When triggered, a constant current sink will discharge the capacitor to a safe voltage in around 5 seconds. The two necessary RC channels are connected to the failsafe through a high-pass filter so that if the signal stops oscillating, the failsafe will trigger. Additionally, a few milliamps are constantly run through the solenoid, so that if it disconnects or fails open, the failsafe will trigger.

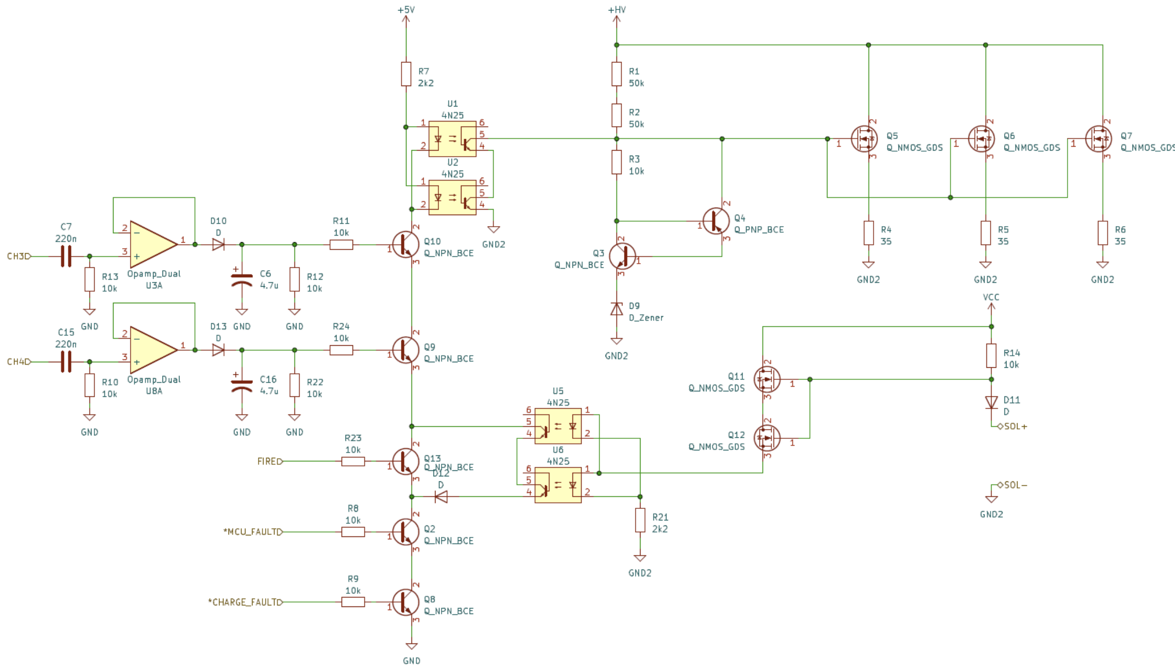

Figure 5. Failsafe Schematic

Simulations:

Once the final schematic was designed, simulations were run in LTSpice to confirm the function of the main circuits. A simulation for the charging circuit was ran with a target output voltage of 300V, the highest voltage this controller is designed to handle. Plotting the output voltage as the capacitor charges shows that the worst-case charge time is about 2 seconds, which is comparable to the spin up time for a conventional spinning weapon.

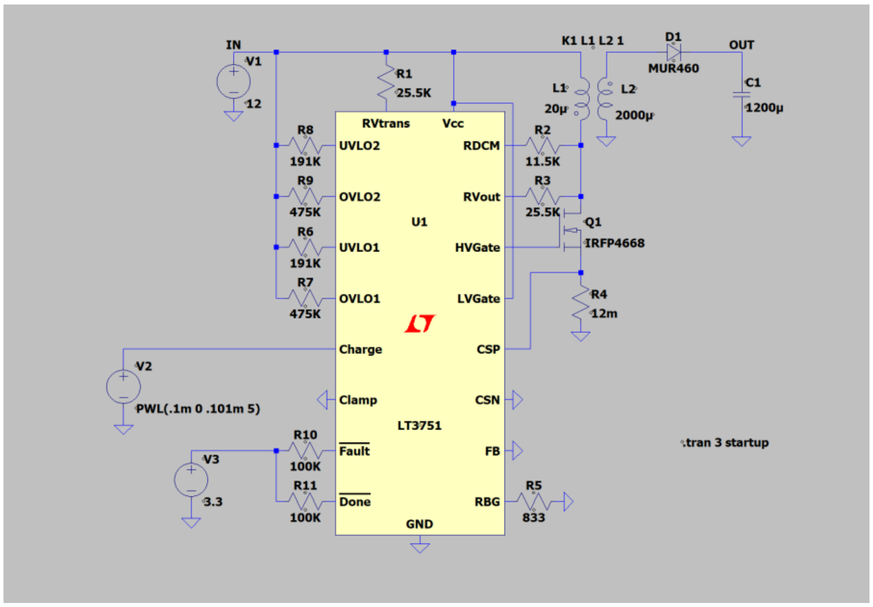

Figure 6. LTSpice Charger Simulation Schematic

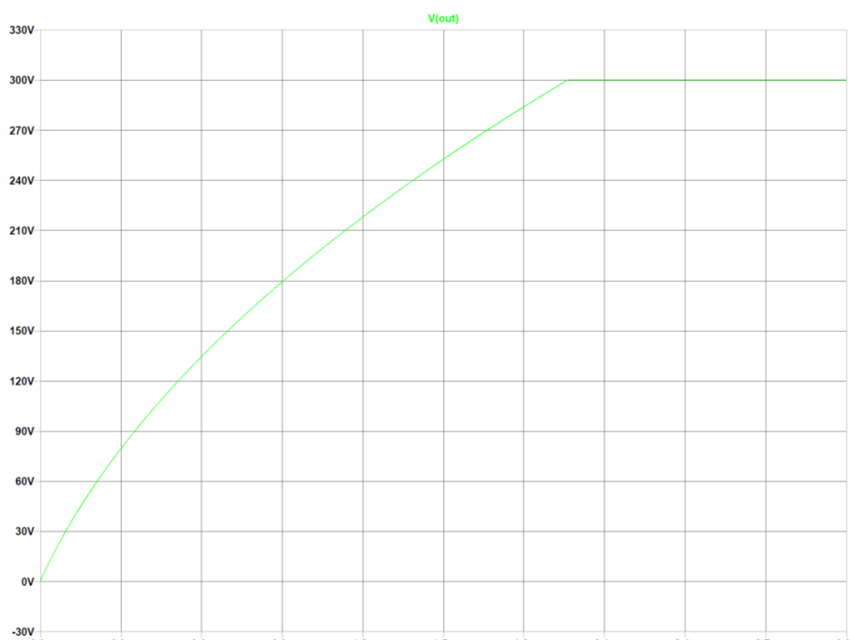

Figure 7. LTSpice Charger Simulation V_{OUT} Plot

A simulation for the firing circuit was run to determine the power output of the solenoid. Comparing the output to the rated output of the chosen solenoid, the Ledex Low Profile 5EC, we can estimate the force of the solenoid. The datasheet for the 5EC shows a minimum force of 10lb with a 10% duty cycle at 210W, and the simulation shows a peak output of 4.5kW with a total duration of 30ms. This is approximately 20x the rated power, which should be more than enough to lift a 6lb robot. Since this solenoid is rated for continuous use, 30ms bursts with at least a 2 second period as limited by the charge time, over the 3 minute duration of a combat robot match the solenoid should withstand being overdriven.

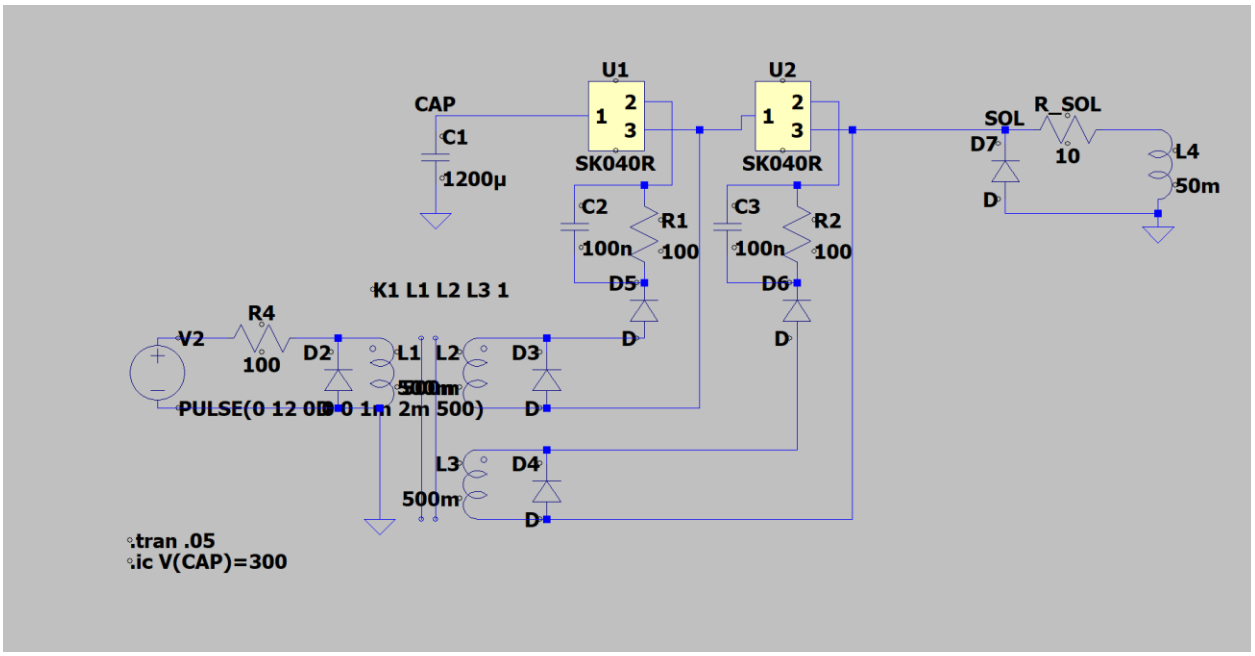

Figure 8. LTSpice Firing Simulation Circuit

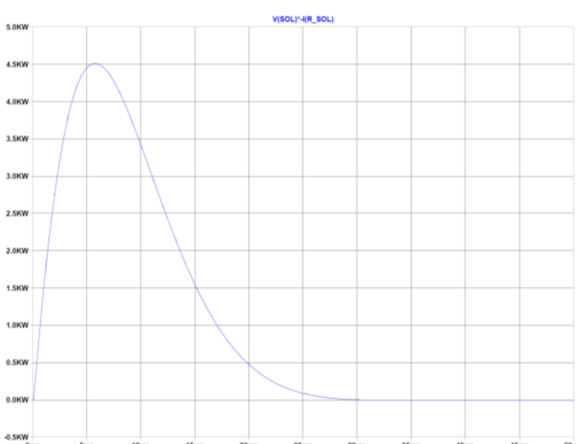

Figure 9. LTSpice Firing Simulation Power Plot

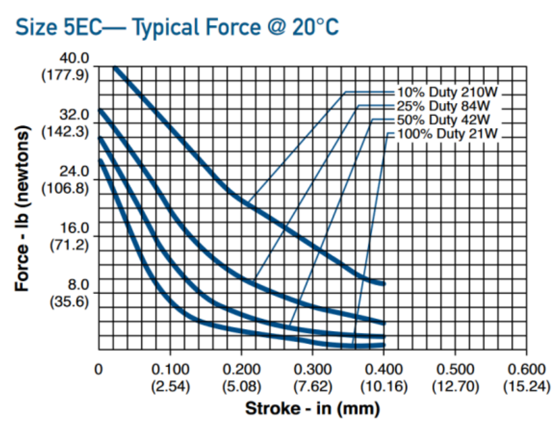

Figure 10. Ledex Low Profile 5EC Typical Force

Two simulations were performed for the failsafe circuit, one for an RC channel failing and one for the solenoid disconnecting. Each simulation starts with the capacitor at 300V and simulates the fault after a 0.5s delay. The first simulation performs 25 pulses with 1ms pulse width and a 20ms period to simulate the RC signal and the second simulation uses a voltage-controlled switch in LTSpice to simulate the disconnection of the solenoid. The simulations showed that both faults triggered the failsafe effectively and the capacitor was discharged to 60V in 1.2s and 9V in 5s, well within the NHRL requirement of 15s.

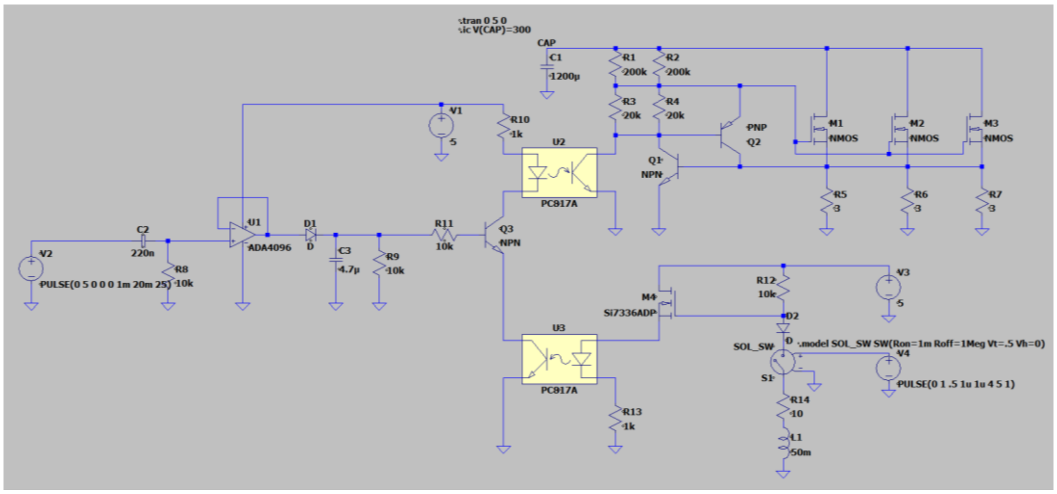

Figure 11. LTSpice Failsafe Simulation Circuit

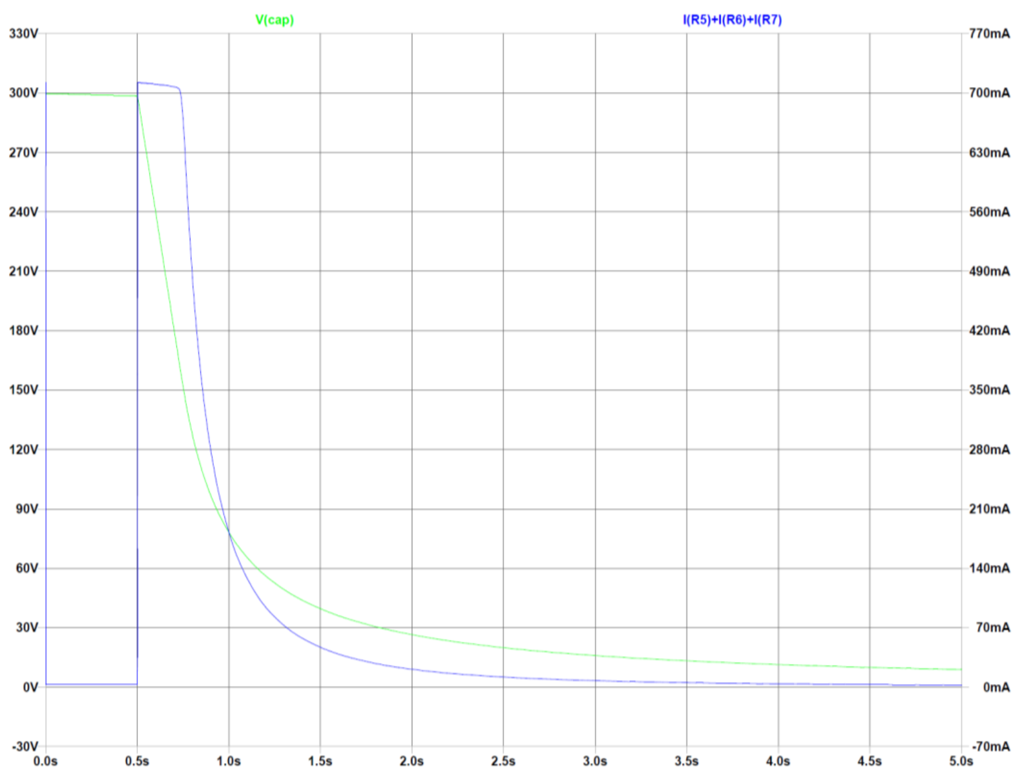

Figure 12. LTSpice Failsafe Simulation Plot

Future Work:

When working with high voltages, safety is the primary concern. With this in mind, further safety precautions should be added. It would be useful to connect the output of the failsafe to the microcontroller so the software can prevent firing in the case of fault. Another important safety feature is redundancy. Some components in the circuit already have redundancies, such as the SCRs in the firing circuit, but there are more places where redundancies should be added. The transistors for each fault in the failsafe should be doubled up if space allows, IO on the microcontroller could be connected to two pins, one on each register, and there should be multiple bleed resistors on the capacitor. Additionally, in order to use high voltages in competition, approval is needed from NHRL, and this could likely include additional safety requirements that they want met.

Another issue is weight. The solenoid weighs 11.5oz, which is about 25% of the robot's weight. Needing a large capacitor in addition to the battery for the robot adds significant weight as well as takes up a lot of space. And the transformer needed for the LT3751 is also a limiting factor. The size of the transformer needs to be chosen to properly balance the weight and the charge time.

Bibliography:

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